PB-237 749

WET SCRUBBER LIQUID UTILIZATION

Konrad Semrau, et al

Stanford Research Institute

Prepared for:

National Environmental Research Center

October 1974

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

EPA-650/2-74-108

WET SCRUBBER LIQUID UTILIZATION

by

Konrad Semrau and Clyde L. Witham

Stanford Research Institute
333 Ravenswood Avenue
Menlo Park, California 94025

Contract No. 68-02-1079
ROAP No. 21ADJ-005
Program Element No. 1AB012

EPA Project Officer: Leslie E. Sparks

Control Systems Laboratory
National Environmental Research Center
Research Triangle Park, North Carolina 27711

Prepared for

OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

October 1974

ia

This report has been reviewed by the Environmental Protection Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-650/2-74-108
2.
3. PB 237 749

4. TITLE AND SUBTITLE
Wet Scrubber Liquid Utilization

5. REPORT DATE October 1974

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Konrad Semrau and Clyde L. Witham

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Stanford Research Institute
333 Ravenswood Avenue
Menlo Park, California 94025

10. PROGRAM ELEMENT NO. 1AB012; ROAP 21ADJ-005

11. CONTRACT/GRANT NO. 68-02-1079

12. SPONSORING AGENCY NAME AND ADDRESS
EPA, Office of Research and Development
NERC-RTP, Control Systems Laboratory
Research Triangle Park, NC 27711

13. TYPE OF REPORT AND PERIOD COVERED Final; Through 7/13/74

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT The report gives results of bench-scale experiments on the ways in which energy consumption, liquid-to-gas ratio (L/G), and water vapor condensation affect the collection efficiency of a conventional, cocurrent-contact, orifice-type particulate scrubber. The test aerosol consisted of spherical particles of ammonium fluorescein with a mass-median diameter of about 0.6 micron. Scrubber collection efficiency was determined and correlated as a function of the effective friction loss across the scrubber. Without condensation or evaporation effects, scrubber efficiency was dependent only upon effective friction loss, with no independent influences of gas velocity, L/G, or contactor orifice size, except possibly in the range of very low gas velocities, L/G, and pressure drops. Large amounts of water evaporation reduced collection efficiencies; but scrubbing hot humid gas with cold water (to produce condensation) significantly increased collection efficiency. The most favorable results were obtained by presaturating the hot humid gas stream before contacting it with cold water.

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Air Pollution Control	13B
Scrubbers	Stationary Sources	07A
Efficiency	Liquid Utilization	14A
Aerosol	Particulates	07D
Liquid Saturation	Energy Consumption	
Condensing	Liquid-to-Gas Ratio	

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 127
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE $5.75/2.25

EPA Form 2220-1 (9-73)

ABSTRACT

A bench-scale experimental investigation was made of the ways in which energy consumption, liquid-to-gas ratio, and condensation of water vapor affect the collection efficiency of a conventional cocurrent-contact particulate scrubber of the orifice type. The test aerosol was composed of spherical particles of ammonium fluorescein with a mass-median diameter of approximately 0.6 micron. The collection efficiency of the scrubber was determined and correlated as a function of the effective friction loss across the scrubber. In the absence of condensation or evaporation effects, the scrubber efficiency was dependent only upon effective friction loss, with no independent influences of gas velocity, liquid-to-gas ratio, or contactor orifice size, except possibly in the range of very low gas velocities, liquid-to-gas ratios, and pressure drops. Evaporation of large amounts of water reduced collection efficiencies, but scrubbing hot, humid gas with cold water to produce condensation significantly increased the collection efficiency. The most favorable results were obtained by presaturating the hot, humid gas stream before contacting it with cold water.

This report was submitted by SRI in fulfillment of Contract No. 68-02-1079, under the sponsorship of the Environmental Protection Agency. Work was completed as of July 13, 1974.

CONTENTS

ABSTRACT iii

LIST OF FIGURES vi

LIST OF TABLES ix

ACKNOWLEDGMENTS x

I SUMMARY AND CONCLUSIONS 1

II RECOMMENDATIONS 5

III INTRODUCTION 7

IV BACKGROUND 9

V METHOD OF APPROACH 14

VI EXPERIMENTAL EQUIPMENT AND PROCEDURES 19

- Bench-Scale Scrubber System 19
- Aerosol Generation 22
- Aerosol Sampling 28
- Aerosol Analysis 30
- General Test Procedure 31

VII RESULTS AND DISCUSSION 33

- Aerosol Generation and Characterization 34
- Ambient Scrubbing Tests 41
- Adiabatic Saturation Tests 54
- Condensing Tests 62
- Vaporizing Tests 69
- General Discussion 74

REFERENCES 86

GLOSSARY 87

CONVERSION FACTORS 90

Contents (concluded)

APPENDIX A LITERATURE REVIEW 91

REFERENCES 99

APPENDIX B ANALYSIS OF EXPERIMENTAL DATA 102

APPENDIX C POTENTIAL COMMERCIAL APPLICATION OF CONDENSATION SCRUBBING 109

TECHNICAL REPORT DATA 116

FIGURES

1 Flowsheet of Experimental Scrubber System 20

2 Electron Micrograph of Aerosol 27

3 Scrubber Performance at Fixed Operating Conditions (Tests EA-26 through EA-47) 38

4 Scrubber Performance Curves for Ambient Scrubbing Tests EA-6 through EA-22 (Aerosol Generator at 35 °C) 39

5 Scrubber Performance Data for Ambient Scrubbing Tests EA-48 through EA-128 46

6 Scrubber Performance Curve for Ambient Scrubbing Tests--Aerosol Generation Rates 350-570 μg/min 47

7 Scrubber Performance Curve for Ambient Scrubbing Tests--Aerosol Generation Rates 750-1000 μg min 48

8 Scrubber Performance Curve for Ambient Scrubbing Tests--Aerosol Generation Rates 1000-1200 μg/min 49

9 Scrubber Performance Curve for Ambient Scrubbing Tests--Aerosol Generation Rates 1200-1500 μg/min 50

10 Scrubber Performance Curve for Ambient Scrubbing Tests--Aerosol Generation Rates 1500-1900 μg/min 51

11 Summary of Scrubber Performance Curves for Ambient Scrubbing Tests 52

12 Correlation of Scrubber Pressure Drop Data for Ambient Scrubbing Conditions 55

13 Scrubber Performance Curve for Adiabatic Saturation Scrubbing--Aerosol A. Gas Temperatures: Inlet = 128.9 °C; Outlet = 71.7 °C 60

Figures (continued)

14 Scrubber Performance Curve for Adiabatic Saturation Scrubbing--Aerosol B. Gas Temperatures: Inlet = 128.9°C; Outlet = 71.7°C 61

15 Scrubber Performance Curves for Condensation Scrubbing (Series I). Gas Temperatures: Inlet = 130.6°C; Outlet = 54.4°C 65

16 Scrubber Performance Curves for Condensation Scrubbing (Series II). Gas Temperatures: Inlet = 129.4°C; Outlet = 37.8°C 66

17 Scrubber Performance Curve for Condensation Scrubbing (Series I and II)--Aerosol A 67

18 Scrubber Performance Curve for Condensation Scrubbing (Series I and II)--Aerosol B 68

19 Scrubber Performance Curve for Condensation Scrubbing (Series III). Gas Temperatures: Inlet = 80.0°C; Outlet = 37.8°C 71

20 Scrubber Performance Curves for Condensation Scrubbing of Gases at Inlet Temperatures of 80° and 130°C--Aerosol B . . 72

21 Scrubber Performance Curve for Vaporization Scrubbing. Gas Temperatures: Inlet = 125.6°C; Outlet = 58.3°C 75

22 Summary of Scrubber Performance Curves for Adiabatic Saturation and Condensation Scrubbing--Aerosol A 76

23 Summary of Scrubber Performance Curves for Adiabatic Saturation, Condensation, and Vaporization Scrubbing--Aerosol B 77

24 Performance of Condensation Scrubbers--Literature Data (Figure 12, Ref. 6A). Range of Present Investigation Added 98

25 Analysis of Residual Deviations--Ambient Scrubbing Tests--Aerosol Generation Rates 750-1000 μg/min 103

Figures (concluded)

26 Analysis of Residual Deviations--Ambient Scrubbing Tests--Aerosol Generation Rates 1000-1200 μg/min 104

27 Analysis of Residual Deviations--Ambient Scrubbing Tests--Aerosol Generation Rates 1200-1500 μg/min 105

28 Analysis of Residual Deviations--Ambient Scrubbing Tests--Aerosol Generation Rates 1500-1900 μg/min 106

29 Analysis of Residual Deviations--Adiabatic Saturation Scrubbing--Aerosol A 108

TABLES

1 Summary of Average Scrubber Test Conditions 16

2 Scrubber Performance Data for Ambient Scrubbing Tests--Aerosol Generator Temperature 35°C 35

3 Scrubber Performance Data for Ambient Scrubbing Tests at Fixed Scrubber Operating Conditions 37

4 Scrubber Performance Data for Ambient Scrubbing Tests . . . 43

5 Scrubber Pressure Drop Data for Ambient Scrubbing Tests . . 56

6 Scrubber Performance Data for Adiabatic Saturation Scrubbing Tests 59

7 Scrubber Performance Data for Condensation Scrubbing Tests--Series I 63

8 Scrubber Performance Data for Condensation Scrubbing Tests--Series II 64

9 Scrubber Performance Data for Condensation Scrubbing Tests--Series III 70

10 Scrubber Performance Data for Vaporization Scrubbing Tests. 73

11 Selected Comparisons of Scrubber Performances at Different Operating Conditions 78

ACKNOWLEDGMENTS

Mr. Charles E. Lapple, Senior Scientist, provided major assistance in the development of the aerosol generation system and the design and procurement of the bench-scale scrubber system, and valuable advice on the conduct of the investigation. Mr. William W. Kerlin, Senior Chemical Engineering Technician, provided valuable assistance throughout the design, procurement, and assembly of the system, and in the subsequent conduct of the experimental work.

The authors wish to express their appreciation for the assistance and cooperation of the Project Officer, Dr. Leslie E. Sparks of the Particulate Technology Section, Control Systems Division of the Environmental Protection Agency.

SECTION I

SUMMARY AND CONCLUSIONS

An experimental investigation was made under laboratory conditions of the performance of a bench-scale orifice scrubber that was generally a replica of many commercial scrubbers of the orifice or modified venturi types. Studies were made of the effects of gas pressure drop, gas velocity, liquid-to-gas ratio, and vaporization and condensation of water vapor. Tests were made at both ambient and elevated temperatures.

All the tests were made with nominally the same test aerosol, which was prepared by nebulizing a solution of ammonium fluorescein and drying the mist particles in a stream of heated air. This procedure produced a spherical, nonhygroscopic aerosol composed almost entirely of submicron particles and having a mass median particle size on the order of 0.6 micron. The performances of the scrubber under various operating conditions were compared on the basis of gas pressure drop (or, more strictly, of "effective friction loss"), and the influences--if any--of other operating variables were inferred from differences in the relationship of collection efficiency to the gas pressure drop.

In fact, the particle-size characteristics of the aerosol generated varied sufficiently to introduce another variable into the experiments, complicating the interpretation of the results. Fortunately, it was found that a mass generation rate of the aerosol generator was a reasonably good correlating factor for the apparent particle-size characteristics of the aerosol, and it was therefore possible to correlate the scrubber collection efficiency data and to interpret their significance.

It appears that the functional relationship between efficiency (actually expressed in terms of transfer units) and the effective friction loss is probably a more sensitive indicator of relative aerosol particle-size characteristics than any of the available methods for measurement of particle size in the submicron region.

Scrubber efficiency tests were carried out under the following conditions:

- Scrubbing of ambient air with water at ambient temperatures
- Scrubbing of hot, humid air (32-35% by volume of water vapor) with hot water at the temperature of adiabatic saturation of the gas stream. This condition simulated the common practice of scrubbing gases with recirculated water, resulting in essentially adiabatic saturation of the gas streams
- Scrubbing of hot, humid air (32-35% by volume of water vapor) with cold water to reach final gas temperatures of 54°C and 38°C, resulting in condensation of most of the water vapor initially present
- Scrubbing of hot, humid, nearly saturated air (32-35% by volume of water vapor) with cold water to reach a final gas temperature of 38°C
- Scrubbing of hot, dry air with hot water, resulting in flashing and evaporation of part of the water and humidification of the air

Results of the foregoing tests yielded the following conclusions:

- Over very wide ranges of gas velocity, liquid-to-gas ratio, and gas pressure drop, the collection efficiency of the scrubber was dependent only upon effective friction loss (essentially equal to the gas pressure drop) and independent of gas velocity and liquid-to-gas ratio (except as these latter factors affected gas pressure drop). (This conclusion did not apply in cases where vaporization or condensation effects were involved.) There may still be some independent effects of gas velocity or liquid-to-gas ratio at very low values of these variables, but if so, the operational region is not one of much practical significance.

- The size of the orifice gas/liquid contactor had no effect on collection efficiency, independent of effective friction loss.
- Condensation scrubbing of the test aerosol produced significant but not very large increases in collection efficiency at a given effective friction loss. The results were qualitatively similar but quantitatively much less than indicated by earlier pilot-plant studies of condensation scrubbing of Kraft recovery furnace fume under similar operating conditions.
- Cooling the outlet gas below 54°C did not increase the condensation scrubbing effect measurably, presumably because only a small additional quantity of water vapor was condensed.
- Adjusting the inlet gas to a nearly saturated condition before contacting with cold water markedly improved the effectiveness of condensation scrubbing.
- Vaporization of scrubbing water tended to reduce scrubber collection efficiency, particularly in the lower range of effective friction loss.
- In practical cases, condensation collection is not an alternative to conventional high-energy scrubbing, but is a supplement that can reduce the scrubbing energy requirements to a greater or lesser degree. Promoting diffusional mass transfer (such as vapor condensation) in practical equipment also requires energy for gas/liquid contacting.

- Because of the requirements for water cooling and possible gas humidification, the net saving of energy in condensation scrubbing may not often outweigh the other associated costs.

- Condensation scrubbing may be, and probably is, warranted under the following conditions:

  (a) Where the waste gas already has a high water vapor content and there is use for low-level heat in the associated process system (e.g., Kraft pulp mills).

  (b) Where the gas must be cooled and dehumidified anyway, for process reasons (e.g., cleaning of blast furnace gas; purification and conditioning of feed gas to contact sulfuric acid plants).

SECTION II

RECOMMENDATIONS

We recommend that priority be given to the following topics for extended study of scrubber performance characteristics:

- A study of the performance characteristics of the orifice scrubber with aerosols of particle sizes ranging from about 2.0 microns down to about 0.1 or 0.2 micron. The aerosols can be produced by the same general technique used in the present investigation: producing a mist of ammonium fluorescein solution and drying the droplets to leave solid particles. Even though the aerosols will not be monodisperse, the median particle sizes can be varied over a fairly wide range by changing the concentration of the solution. The practical lower particle size is set by the coincident lowering of the quantity of aerosol. This program should provide badly needed information about the relationship of scrubber collection efficiency to both contacting power (effective friction loss) and aerosol particle size. We expect that it should also elucidate, or help to elucidate, some currently unexplained phenomena that sometimes appear in the scrubbing of very fine aerosols--most specifically, a rapid falling off of collection efficiency in the low contacting power range.

- An investigation of the comparative performances of different classes of gas/liquid contactors as functions of contacting power. The same test aerosol, or aerosols, should be used throughout.

Particular attention should be given to two classes of contactors: (1) those deriving contacting power from the energy of the liquid stream, and (2), those deriving contacting power from a mechanically driven rotor. The tests should aim at establishing unequivocally whether contacting power so derived is fully equivalent to that derived from the gas stream in the form of friction loss (or pressure drop).

It is possible that with mechanically driven rotors, a larger part of the total power input can be effective as contacting power than in the other classes of contactors. This should afford saving in total power input if contacting power is fully equivalent for all the types of contactors.

- If a field demonstration of condensation scrubbing in a potential commercial application is desired, we recommend that a study be made of the scrubbing of Kraft recovery furnace fume. The test scrubber unit should have a gas flow capacity of about 850 m^3/hr (500 ft^3/min) or, at most, of 1700 m^3/hr (1000 ft^3/min), which is small enough to permit ease of experimental operation, or modification without inordinate costs or time requirements. The fan capacity should be sufficient to handle scrubber pressure drops up to 1800 mm WC (70 inches WC). Heat exchangers should be included for cooling recirculated scrubbing water.

Two scrubber units should be provided in series, each with gas/liquid contactor and liquid entrainment separator. The first unit should be designed for low-energy contacting, primarily to cool and saturate the gas by scrubbing with recirculated water. The second scrubber should be equipped for high-energy contacting with cold water or cold recirculated brine. The scrubbers should be of the variable-orifice type with cyclone entrainment separators. However, there should be provisions for substituting a pipeline contactor for the variable orifice.

SECTION III

INTRODUCTION

GENERAL

In the operation of particulate wet scrubbers, the collection of progressively finer particles and an increase in the efficiency of collection of particles of any size are both associated with increased power consumption. Current trends in the requirements for control of particulate air pollutants emphasize both the collection of fine particles (primarily those in the submicron range) and higher efficiencies in the collection of particles of all sizes. It can therefore be anticipated that future particulate scrubber installations will have increasing power requirements. Hence, it is important to investigate any possible means for minimizing those power requirements.

OBJECTIVES

The broad objective of this investigation was to study the ways in which energy consumption, liquid-to-gas ratio, and condensation of water vapor affect the collection efficiency of particulate scrubbers. The original contract called for emphasis on the effects of liquid rate and energy consumption. However, at the request of EPA, the emphasis of the program was shifted to the effects of water vapor condensation on the collection efficiency of conventional scrubbing equipment.

The revised scope of work included the following tasks:

(1) Review and assessment of the published literature and available unpublished information on the effects of liquid-to-gas ratio; method of water injection, energy consumption, and water condensation and evaporation on the efficiency of particulate scrubbers.

(2) Conduct of a bench-scale experimental study of particle collection of a conventional coccurrent-contact particulate scrubber of the modified venturi or orifice type. Emphasis was to be placed on enhancing the collection efficiency by use of condensation techniques.

(3) Recommendation of a potentially suitable commercial application for condensation-scrubbing techniques, using basically conventional scrubbers of the venturi or similar types.

(4) Development of a plan for a pilot-plant study of the scrubbing process in the recommended commercial application, including preparation of a process design, an experimental program, and a cost estimate.

SECTION IV

BACKGROUND

It is now widely, though not universally, accepted that an increase in the efficiency of particulate scrubbing is associated with an increase in power consumption, and that the power consumption associated with attainment of a given collection efficiency increases with decrease in the particle size of the particulate matter. Recognition and acceptance of these facts, and use of them in design procedures, have formed the basis for the recent greatly increased use of scrubbers for collection of fine particles. Relatively high power consumption is thus characteristic of scrubbers, although they may exhibit definite advantages in other respects for numerous applications. As requirements grow for higher collection efficiencies on finer aerosols, the associated increases in scrubber power consumption are a growing economic burden, and it becomes increasingly important to seek ways to decrease the power consumption if such can be found.

The number and diversity of scrubber designs is such as to defy any entirely self-consistent or truly descriptive system of classification, and it is even more difficult to try to describe the various devices in terms of performance mechanisms. However, since power consumption is a major characteristic of scrubbers, it is possible to characterize various units according to the way in which power is applied to the scrubbing process.

There are basically three ways of applying power in scrubbers:

(1) From the energy of the gas stream

(2) From the energy of the liquid stream

(3) From a mechanically driven rotor.

When the energy is derived from the gas stream, the amount consumed takes the form of gas pressure drop, and must be supplied by a fan. Energy may be supplied to a liquid stream by three methods: (1) applying pressure to the liquid stream, (2) applying to the liquid the energy of a compressed gas (e.g., compressed air, stream), and (3) applying to the liquid energy from a mechanically driven spray generator. The net effect in each of the three cases is that kinetic energy is imparted to the liquid stream being injected into the gas stream being scrubbed.

In a mechanical scrubber, both the gas and liquid streams pass through the rotating member. This member, which may be a modified fan, frequently serves also to provide draft for the scrubber. In such case, the power input to the drive shaft can be considered to have two components, only one of which is related to scrubber efficiency.

It should be noted that the power consumption that is directly related to scrubber efficiency is not the gross power input to the scrubber, which may include power consumption due to motor, pump, or fan inefficiencies, or power input that leads to increases in the kinetic energy or pressure head of the gas stream. The criterion of scrubber efficiency is that portion of the power consumption that is consumed in the gas-liquid contacting process and is ultimately converted to heat through turbulence; this is termed "contacting power".[4] (A review of the pertinent background literature is presented in Appendix A.)

The "contacting power rule" proposes that energy applied to the scrubbing process by any of the three basic methods is equivalent, and that the efficiency obtained on a given aerosol at a given contacting power should be essentially independent of the scrubber design and of the way, or combination of ways, in which the contacting power is applied. A very substantial body of information that supports this hypothesis has now been accumulated, particularly for the types of scrubbers in which contacting power takes the form of gas pressure drop. There is considerable evidence to indicate that contacting power derived from spray nozzles is also equivalent. The equivalence of contacting power from mechanically driven rotors has not been fully demonstrated, but is mostly inferred by analogy.

A scrubber design that could attain significantly higher efficiency at a given power consumption than other competitive designs would have a clear advantage. However, no such advantages for specific devices have so far been clearly demonstrated, although they are frequently claimed. A large part of the remaining uncertainty about the validity of such claims results from the lack of test results for different devices taken under precisely the same conditions, which are currently the only available unequivocal basis for comparison.

One of the uncertainties in scrubber performance is the degree to which liquid-to-gas ratio may affect efficiency, independent of contacting power. It must be assumed that some lower liquid rate will exist below which scrubbing efficiency will be lost. Some investigators have reported that liquid-to-gas ratio has important--or, at least, significant--effects on the performance of venturi scrubbers. Others have found little or no independent effect. (See Appendix A.)

In the case of spray scrubbers using hydraulic spray nozzles, the presumption is that a given contacting power and collection efficiency may be attained alternatively by use of a relatively small volume of spray at high pressure, or of a larger volume of spray at correspondingly lower pressure. The possible limitations of this hypothesis have not been systematically studied, although such data as are available tend to confirm it.

The possibilities of channeling of liquid and gas flows appear to be much more serious in the case of some spray scrubbers than in the case of the venturi, orifice, or pipeline types. In the latter three types, good liquid dispersion appears generally to be inherent, except possibly at very low liquid rates or gas velocities. In the case of spray scrubbers, it is possible to visualize arrangements in which channeling effects might be severe.

The actual mechanisms through which power consumption leads to particle collection can, for the present, only be inferred in very general terms. It seems reasonable that the actual deposition of particles involves primarily the collision of the particles with spray droplets formed in the scrubber, and that the primary deposition is inertial. The correlation of collection efficiency with power dissipation strongly indicates that fluid turbulence governs the droplet and particle motions that present the opportunities for collisions. The observation that the contacting power-collection efficiency relationship is so similar even for radically different types of devices suggests in addition that the scrubbing process is essentially the same in all of the scrubbers. The dissipation of the power is evidently a gross, overall measure of the atomization of the liquid and the turbulent circulation of drops and particles in the gas stream.

The experience to date suggests that there is no way to increase scrubber collection efficiency significantly at given levels of contacting power so long as only the inertial mechanism can be used. It may be practical under some circumstances to increase the scrubber collection efficiency by superimposing additional particle collection mechanisms on the process through use of condensation phenomena. One such phenomenon is the condensation of moisture on the particles as nuclei, which will increase the effective particle size and, hence, the effectiveness of inertial deposition. The other known phenomenon in this category is Stefan flow. Both of these phenomena have been demonstrated (see Appendix A). The major uncertainty has been in the quantitative increase in collection efficiency attainable by their use, particularly in conventional scrubbing equipment. Improvements in the efficiency of conventional equipment resulting from condensation effects have been reported fairly frequently on a qualitative basis. However, it has not often been demonstrated clearly that part or all of the reported effects may not have resulted from other, coincident factors.

It has also been known from theoretical considerations and laboratory experiments that where a liquid is evaporating at a surface, the resulting Stefan flow tends to inhibit particle deposition. Hence, there should be a corresponding tendency to reduction of collection efficiency in scrubbers in which the scrubbing liquid is vaporizing. Apparently there has been no effort made prior to the present investigation to determine how important this phenomenon may be in practical scrubbing systems.

SECTION V

METHOD OF APPROACH

The basic method of approach used in this investigation was empirical, although it was guided qualitatively by theoretical considerations. The particulate scrubbing process is obviously extremely complex, and presenting an adequate and detailed picture of it is a highly intractable problem from both theoretical and experimental viewpoints. A number of workers have attempted to develop practical models of scrubber operation, but have necessarily been obliged to simplify the models and to introduce assumptions and estimates that are of more or less questionable validity. In general, it has not yet been possible to subject the models to adequately critical experimental verification.

So far, the correlation of the experimentally determined collection efficiency as a function of contacting power has proved to be the most reliable as well as the most practical approach to design of actual installations. There has been no satisfactory experimental determination of the relationship between collection efficiency and contacting power for particles of specific, discrete sizes. Attempts to do this have been largely frustrated by the problems of measuring the size and quantity of particulates in a mixture of particles of different sizes, and by the difficulties of generating particles of discrete and controlled sizes. In fact, the collection efficiency/contacting power correlation curve for a given scrubber appears to be a much more sensitive indicator of the particle size and particle-size distribution of an aerosol--or of changes in these quantities--than are the available methods for measuring low-micron and submicron particles. Of course, the scrubber does not "measure" the particle size. However, if scrubber performance curves can be established experimentally for discrete particle sizes, it should then be possible to make a reasonable quantitative or semi-quantitative interpretation of the size characteristics of an aerosol from the corresponding scrubber performance curve.

In the present investigation, the approach was to use a single aerosol in tests of a bench-scale scrubber over a range of gas pressure drops at various controlled operating conditions (see Table 1). For each such operating condition, a correlation (graphical) was developed between the collection efficiency (actually expressed as the number of transfer units) and the contacting power. (See Glossary.) From comparison of the different correlation curves, the incremental effects of condensation and vaporization were deduced.

In the general case, contacting power is best expressed in terms of power per unit of volumetric gas flow rate.[4] However, in many scrubbers of the venturi or orifice types, including the one used in this investigation, the contacting power is essentially equivalent to the gas pressure drop, and can be expressed conveniently in the same units (e.g., millimeters of water). However, the contacting power is not in principle (or in fact, in some cases) necessarily equal to the total pressure drop across a scrubber.[4] To emphasize the distinction, the quantity equivalent to contacting power has been termed the "effective friction loss" in this report, even though it has been taken to be equal to the gas pressure drop and has been expressed in the same units; mm WC (millimeters of water column).

The average operating conditions used for the various scrubber test series are summarized in Table 1. In the "Ambient" tests, ambient air was in most cases scrubbed with water from the supply line, without recirculation. In a few tests, the scrubbing water was recirculated. The entering air was actually heated slightly above the ambient temperature by its mixing with the small flow of heated air containing the aerosol (see Section VI). When the scrubbing water was recirculated,

Table 1

SUMMARY OF AVERAGE SCRUBBER TEST CONDITIONS

Operating Condition	Gas Temperatures (°C and °F)		Water Temperatures (°C and °F)		Gas Moisture Content (g/g dry air)	
	Inlet	Outlet	Inlet	Outlet	In	Out
Ambient	25-40°C 77-104°F	19-38°C 67-100°F	11-39°C 51-102°F	11-38°C 51-100°F	0.006-0.010	0.008-0.043
Adiabatic saturation	128.9°C 264°F	71.7°C 161°F	73.9°C 165°F	73.9°C 165°F	0.317	0.369
Condensing						
I	130.6°C 267°F	54.4°C 130°F	13.3°C 56°F	54.4°C 130°F	0.327	0.117
II	129.4°C 265°F	37.8°C 100°F	12.2°C 54°F	33.9°C 93°F	0.315	0.0404
III	80.0°C 176°F	37.8°C 100°F	12.8°C 55°F	33.9°C 93°F	0.322	0.0481
Vaporizing	125.6°C 258°F	58.3°C 137°F	73.3°C 164°F	58.3°C 137°F	0.007	0.149

it also was heated by contact with the warmer air as well as by the turbulence generated in the water circulating pump. The gas and water temperatures and the gas moisture contents are shown as ranges rather than as averages.

For the test series designated as "Adiabatic Saturation", "Condensing", and "Vaporizing", the temperatures and gas moisture contents shown are averages. The temperatures were actually read to 1° F, and the Fahrenheit temperatures were converted into Centigrade values to the nearest 0.1° C. The tabulated Centigrade temperatures do not imply a precision of measurements.

In the Adiabatic Saturation tests, an attempt was made to feed the scrubbing water at a temperature as nearly equal as practical to the adiabatic saturation temperature of the entering gas stream; the scrubbing process was thus intended to approximate an adiabatic humidification (and saturation) of the gas stream, simulating the scrubbing of the gas with recirculated water. The inlet water vapor content was selected as representative of that in a considerable number of waste gases of industrial importance.

In the Condensing tests, Series I and II, the inlet gas was nominally the same as in the Adiabatic Saturation tests, but it was scrubbed with sufficient cold water to condense water vapor and bring the exit gas temperature down to desired levels. In Series III, the procedure was the same except that the inlet gas was only of the order of 5° C above the adiabatic saturation temperature, so that the tests approximated scrubbing of a presaturated gas.

In the Vaporizing test series, the hot, dry inlet gas was scrubbed with hot water. Upon injection into the hot gas, some of the water flashed to vapor because of its level of sensible heat content. More of it was thereafter evaporated by the hot gas. The Vaporizing tests were designed to indicate the possible extent to which particle collection may be inhibited by Stefan flow effects.

SECTION VI

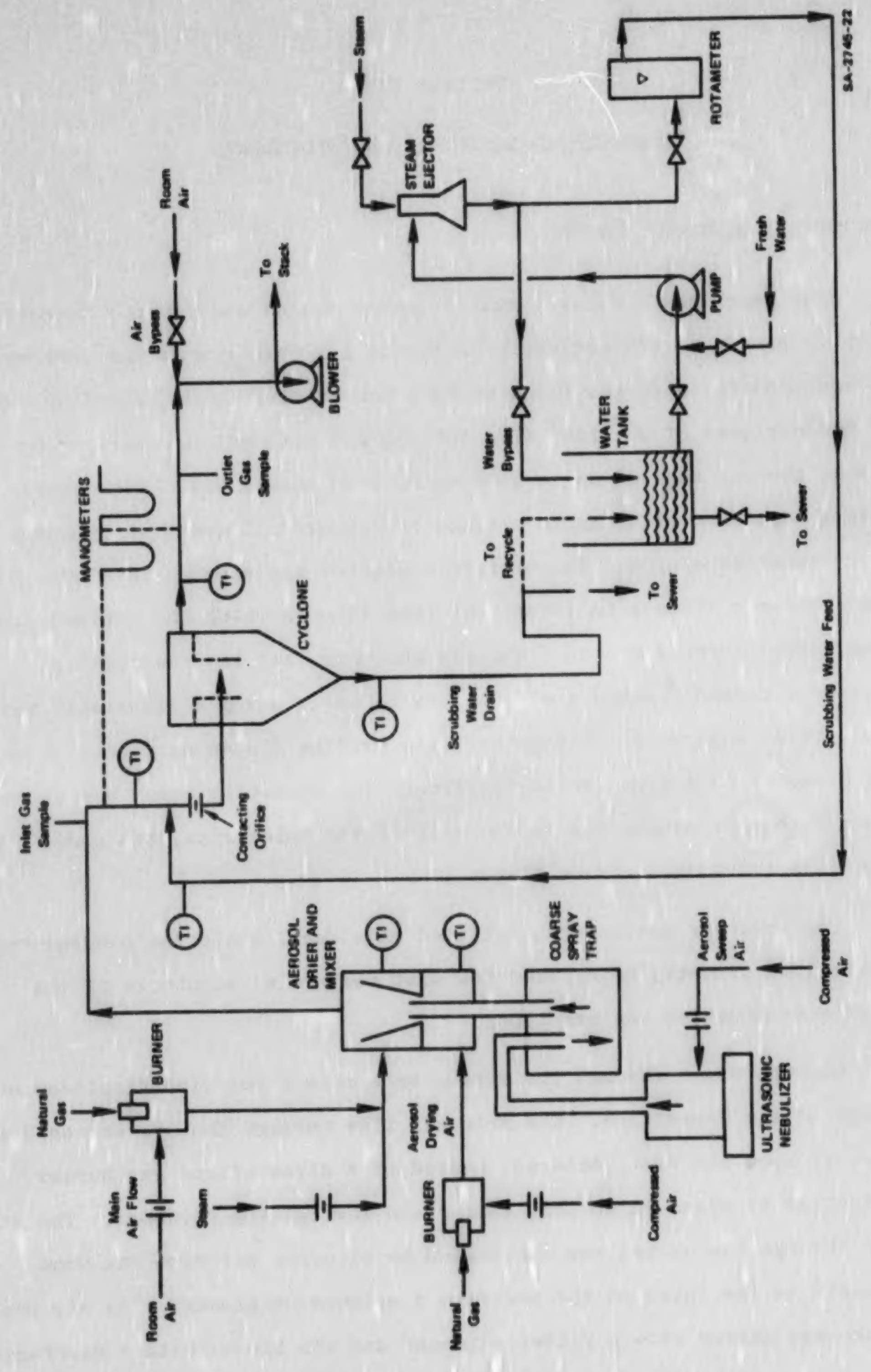
EXPERIMENTAL EQUIPMENT AND PROCEDURES

BENCH-SCALE SCRUBBER SYSTEM

The bench-scale experimental scrubber system used in the investigation is portrayed schematically in Figure 1. This system was designed to accommodate inlet gas flows of up to about 4200 liters/min (150 CFM) at temperatures of 20°-150° (70°-300°F), and with gas pressure drops across the scrubber of up to 3000 mm WC (120 inches WC). The scrubber itself consisted of a simple orifice contactor followed by a cyclone entrainment separator. The orifice contactor was mounted in a horizontal plane between flanges in a vertical line through which the gas and scrubbing water flowed downward. The gas and water leaving the orifice contactor passed through a mitre elbow before flowing horizontally into the cyclone separator. Interchangeable orifice plates were used to vary the diameter of the contacting orifice. The scrubbing water was introduced through a single tap in the wall of the inlet line, two pipe-diameters above the orifice plate.

The scrubber design thus followed on a small-scale the general configuration currently being used for most commercial scrubbers of the orifice or modified venturi types.

Gas was drawn through the system by a rotary positive-displacement blower of the Roots type. The main air flow through the system was drawn directly from the room, metered, heated by a direct-fired gas burner, humidified by steam injection, then drawn through the scrubber. The air flow through the system was controlled by bleeding air from the room directly to the inlet of the positive displacement blower. The air bypass intake was fitted with a filter-silencer and the blower with a discharge



Room Air
Main Air Flow
Natural Gas
BURNER
Steam
Natural Gas
BURNER
Compressed Air
Aerosol Drying Air
AEROSOL DRIER AND MIXER
TI
TI
COARSE SPRAY TRAP
ULTRASONIC NEBULIZER
Aerosol Sweep Air
Compressed Air
TI
Inlet Gas Sample
TI
Contacting Orifice
TI
Scrubbing Water Drain
CYCLONE
TI
MANOMETERS
Outlet Gas Sample
To Recycle
To Sewer
Air Bypass
Room Air
BLOWER
To Stack
Water Bypass
WATER TANK
To Sewer
STEAM EJECTOR
Steam
PUMP
Fresh Water
ROTAMETER
Scrubbing Water Feed
SA-2745-22

FIGURE 1 FLOWSHEET OF EXPERIMENTAL SCRUBBER SYSTEM

silencer. However, the main air stream entering the system was not filtered; since the test aerosol was measured by a specific fluorometric method, the presence of atmospheric dust in the room air did not interfere with the determinations of scrubber efficiency.

The scrubbing water system was so arranged that water could be sent through the system in a single pass; in such a case the water supply line pressure was usually sufficient to overcome line resistance without use of the pump. Alternatively, the scrubbing water could be recirculated by use of the water holding tank and the pump. When hot water was used in scrubbing, the steam ejector could be used to heat the water whether it was used in a single pass or was recirculated. The water in the holding tank could be heated by recirculation through the steam ejector and also by another steam siphon not indicated in Figure 1.

The scrubber and cyclone were elevated so that the water could be discharged by gravity at the highest gas pressure drops used in the tests. The water was discharged through a seal loop either directly to the sewer or to the holding tank for recycle.

Contactor orifices of three different diameters were used in the investigation: 2.54, 3.81, and 4.45 cm (1.0, 1.5, and 1.75 inches). The line in which the contactor orifice was located was made from 2½-inch stainless steel tubing. The cyclone separator, which was originally built and used in an earlier investigation, was 45.7 cm (18 inches) in diameter, with an inlet 7.6 cm (3 inches) in diameter and an outlet 10.2 cm (4 inches) in diameter. It was actually larger than necessary to handle the gas flows used in the present investigation. The general design was the same as that used by Lapple and Kamack[3] for a semiworks scrubber unit. The main inlet air header, including the orifice meter section was made from 15.2-cm (6-inch) stainless steel tubing.

The main air flow was measured with a standard-design orifice meter equipped with square-edged orifices and fitted with radius taps located

1 pipe diameter upstream and ½ pipe diameter downstream of the orifice plate). Steam flows were measured with critical-flow orifice meters, with Bourdon gages used to measure the steam pressures. The water flows were measured with rotameters of appropriate ranges.

System pressures and pressure drops were measured with U-tube manometers filled with xylene or mercury, as demanded by the ranges of pressures involved. The gas and water temperatures were measured with dial thermometers of the bimetal type.

AEROSOL GENERATION

The aerosol generation system is also indicated schematically in Figure 1. The original cloud of droplets was generated from a solution with an ultrasonic nebulizer. A small flow of air swept the mist upwards through the chimney above the nebulization chamber and through a trap for removal of any residual coarse spray droplets. The fine mist then rose straight upward through a section of 1-inch IPS pipe and entered the lower end of a conical diffuser section which was located concentrically within the 15.2-cm (6-inch) riser that carried the main airflow upward to the scrubber. Another small flow of heated drying air also entered the lower end of the conical diffuser section through the annular space around the pipe carrying the mist. The mist and heated air mixed with the diffuser section, where the water was evaporated from the droplets, leaving solid aerosol particles. The resulting aerosol stream emerging from the upper end of the diffuser was then mixed with the main air stream, which flowed through the annular space between the upper end of the diffuser and the 6-inch riser.

The sweep air to the nebulizer was taken from a compressed air line and metered to a constant 14.2 liters/min (0.5 ft^3/min) in all tests with a critical-flow orifice. The aerosol drying air was also metered with a critical-flow orifice to a constant rate of 84.9 liters/min (3 ft^3/min). It was heated by a small direct-fired gas burner to a temperature in the range of 170-200°C. The aerosol generation system was developed in separate but parallel and continuing effort supported by Stanford Research Institute. An ultrasonic type of nebulizer was chosen to produce the original mist of solution droplets, because previous experience at Stanford Research Institute and elsewhere[1] had indicated that the ultrasonic device produced a narrower band of droplet sizes (with a median diameter of about 6 microns) than other types of atomizers, and should therefore produce a more uniform aerosol. The ultrasonic nebulizer is used commercially to prepare mists of therapeutic agents in a particle-size range for effective inhalation therapy.[1,6] It has also been employed to prepare sodium chloride aerosols for testing respirator filters,[2] a use comparable to that in the present investigation.

The basic element of the generator system was a commercial ultrasonic nebulizer (DeVilbiss Model 35A). The original plastic nebulization chamber and chimney were replaced by one made from stainless steel. The height of the chimney was increased from that of the original to provide a greater space in which oversized spray droplets could disengage from the air stream and settle back into the liquid sump. The solution to be nebulized was supplied to the nebulization chamber from an overhead reservoir fitted with a gravity feed system so vented as to maintain a constant liquid level in the chamber (not indicated in Figure 1).

Reports by other users and some preliminary experiments had indicated that increases in the temperature of the liquid being nebulized also increased the output of the generator. After some of the preliminary experiments with the scrubber had been carried out, it was decided to stabilize the temperature of the liquid at a temperature somewhat above any room temperatures expected to be encountered. The metal chimney of the nebulizer was therefore wrapped with heating tape, and the current to the tape was regulated by a controller operating off the output of a thermistor immersed in the liquid in the nebulizer. The liquid temperature was set at 35°C. It was then found that operating at the higher fixed temperature neither stabilized the output of the generator nor clearly increased it (see Section VII). The heating system was therefore removed and the generator was operated thereafter at room temperature.

In another attempt to stabilize the generator output, a harmonically compensated voltage regulator was inserted in the electrical power supply line to the generator. The voltage regulator was continued in use, but apparently had no effect in stabilizing the generator output.

Despite the attempts to stabilize generator output by fixing the temperature and the level of the liquid in the generator and by regulating the voltage of the electrical supply, fluctuations and shifts in the generator output continued. The nature and consequences of these changes are discussed below in Section VII.

The maximum liquid nebulization rate for the generator was about 3 cm^3/min. Since it was desired to produce a well-dispersed aerosol with a mass-median size of about 0.5 - 0.8 micron, it was necessary to use a dilute solution of the aerosol material. Hence, the concentration of the aerosol in the scrubber air stream was necessarily low. This condition was desirable for minimizing flocculation of the aerosol, but also required a sensitive method of analysis if the necessity of long sampling times to collect large samples was to be avoided. For this reason, a fluorescent dye was highly advantageous. Reports in the literature indicated that ammonium fluorescein produced a spherical, nonhygroscopic, and readily analyzed aerosol.[7,8]

In a preliminary investigation a 10% solution of ammonium fluorescein was nebulized in the ultrasonic nebulizer and the droplets were dried in an air stream to produce dry particles which were collected on a membrane filter and examined under a light microscope. The particles were easily discerned to be spherical, and showed no sign of hygroscopicity when left exposed to atmospheric air. The particle sizes fell mostly in the range of 1 to 5 microns with an apparent mass-median diameter of about 3 microns (as judged by visual observation in the microscope). From these observations it was judged that nebulizing a 0.1% ammonium fluorescein solution should produce an aerosol with a mass-median diameter of about 0.6 - 0.8 micron that would be suitable for the scrubber testing program.

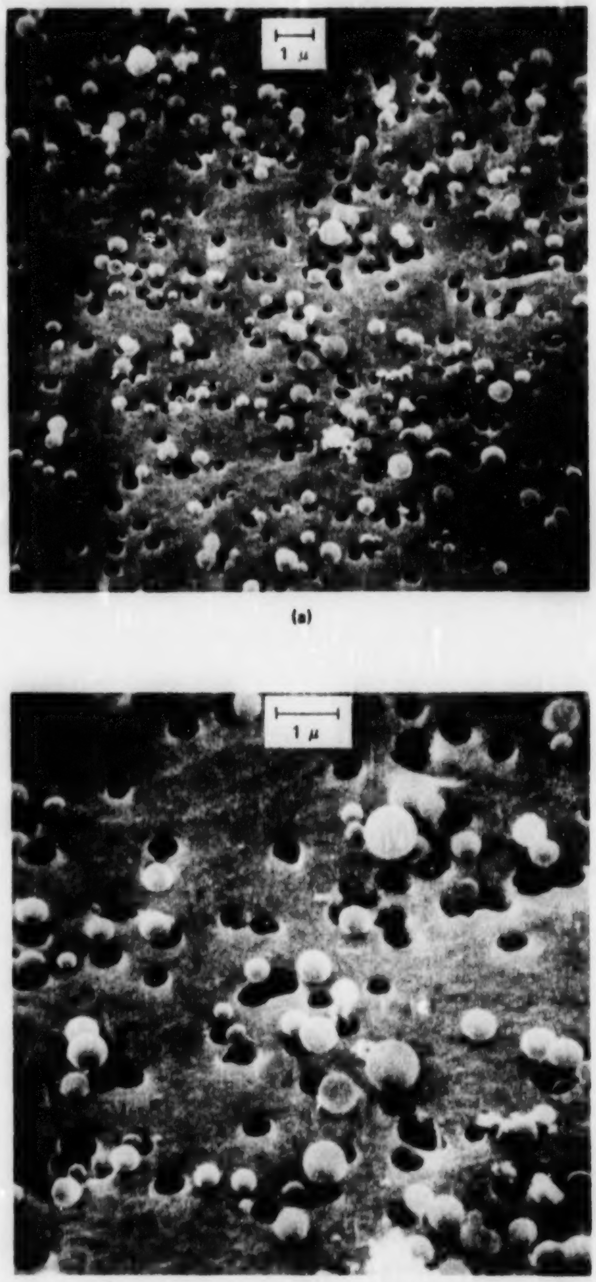
The ammonium fluorescein solution was first prepared at a concentration of 1% by weight. The appropriate amount of fluorescein (acid form) was weighed out and dissolved in a quantity of ammonium hydroxide solution equivalent to four moles of ammonium ion per mole of fluorescein (acid form). Water was added to make up the solution to the appropriate total weight (and volume). This stock solution was stored in glass and in darkness. The 0.1% solution for experimental use was made up from the stock solution by dilution.

One possible factor in the variation in aerosol generation rates, which would also affect particle size, is concentration of the solution in the nebulizer by evaporation. The sweep air to the nebulizer, taken from a compressed air source and not humidified after expansion, was dry. Although it had been expected that most of the moisture evaporated into the sweep air would be absorbed from the aerosol mist being formed, it was later found that the concentration of ammonium fluorescein in the nebulizer solution did increase, demonstrating that at least part of the water was evaporated from the liquid remaining in the nebulizer. It was estimated that the concentration in the nebulizer should reach an equilibrium level about 30% above that of the feed solution, assuming that the liquid remained at room temperature. When analyses revealed that the nebulizer liquid was being concentrated, some values approximating the estimated equilibrium concentration were obtained. Thereafter, each day's operation was started with fresh feed solution in the nebulizer.

Some of the variation in the aerosol generation rate may have been related to changes in the solution concentration, but the pattern of the variations did not correspond to the reasonable course of gradual concentration of the solution. A series of measurements of aerosol generation rate was also made with known nebulizer solution concentrations ranging up to 16% above the nominal feed concentration. (This work was done as part of the Institute-supported program on aerosol generation.) The observed variations in generation rate were much greater than could be accounted for by the changes in the nebulizer solution concentration and did not, in fact, appear to be significantly correlated with them.

Overall, it does not appear likely that variations in the concentration of the nebulizer solution were responsible for more than a minor part of the observed variations in the aerosol generation rate.

Near the end of the investigation, when the generator was producing "Aerosol B" (see Section VII), samples were taken of the aerosol collected on Nuclepore membrane filters with 0.4-micron pores. A gold-palladium film (less than 100 Angstrom units thick) was vacuum deposited on the filter to provide a conducting surface, and photomicrographs were obtained with a scanning electron microscope. Photomicrographs of one sample taken at magnifications of 5,000 X and 10,000 X are shown in Figure 2. These show a range of particle diameters from about 0.2 to 0.8 micron, with a probable mass median of about 0.6 micron. Examination of the same membrane under a light microscope, covering a very much larger field, indicated the presence of a small number of larger particles, up to perhaps 1.5 microns in diameter. These few large particles apparently contributed only a small fraction to the total size distribution by mass.



(a)

(b)

SA-2745-20

FIGURE 2 ELECTRON MICROGRAPH OF AEROSOL

At the time that the photomicrographs of Figure 2 were taken, it was known that the particle size of the aerosol produced by the generator was variable, but the variations were probably too small to be readily detectable by any of the available methods of size measurement. They were, however, revealed by the performance of the scrubber. The photomicrographs do illustrate that the particle size of the aerosol was in the expected range.

AEROSOL SAMPLING

The aerosol was sampled at the inlet and outlet of the scrubber (see Figure 1), using 25-mm Nuclepore membrane filters in Nuclepore holders. The membrane holders were made of polycarbonate plastic, for which the upper limit of operating temperature was about 140°C (285°F). The inlet piece of the filter holder was machined out to expose almost the entire effective diameter of the membrane directly to the incoming gas. The holders were turned to face directly into the gas stream being sampled, but no effort was made to sample isokinetically, because the aerosol was too small for sampling to be appreciably affected by inertial effects.

Initially, tests were made with two filter discs placed in series in each holder, with both discs being analyzed. Tests were made with membranes with 1.0, 0.8, 0.6, and 0.4-micron pores. The standard procedure finally adopted was to use a single disc with 0.6-micron pores to provide an acceptable combination of efficiency and resistance to flow.

The filter holders were immersed in the gas stream to be sampled so that the filter would be at the gas stream temperature and water vapor condensation would be avoided until the gas sample had passed through the filter. The gas stream was then drawn through a condenser for removal of water vapor and cooled to ambient temperature before being metered in a critical flow orifice. Vacuum was supplied by a mechanical vacuum pump. Sampling rates in the range of 2-10 liters/min were used, with the highest rates at the scrubber outlet where the aerosol concentration was lowest.

The precision of aerosol sampling was checked by operating two samplers in parallel at each of the sampling points. At the scrubber outlet, 11 pairs of runs were made; the deviations between the paired samples ranged from 1.1 to 8.9%, and averaged 3.5%. At the scrubber inlet, only three pairs of runs were made; the deviations ranged from 1.6 to 12.5% and averaged 6.1%. Another four paired samples were taken with one sampler operated at each position, inlet and outlet, and with no water fed to the scrubber. In two of these paired runs, the measured outlet aerosol concentration was higher than the inlet concentration. The deviations ranged from 1.9 to 5.6%, with an average of 2.9%. Evidently, the scrubber, operated dry, did not collect any of the aerosol, at least within the precision of measurement.

Subsequently, material balance runs were made as part of an Institute-supported program for development and evaluation of the aerosol generation system. The inlet and outlet air streams were sampled in the usual manner, and integrated samples of the outlet scrubbing water were also obtained. The quantity of inlet aerosol measured by sampling the inlet air was compared with the sum of the quantities leaving the scrubber in the exit air and collected in the water. This comparison involved not only the precision of sampling but that of the measurement of the air and water flow rates as well. Positive and negative deviations were about equal in number, ranging from 0.9 to 16.7% with an average of 5.0%.

From these results, it appears that the average error in aerosol sampling did not exceed 5 to 6% and that individual errors seldom exceeded 10%.

AEROSOL ANALYSIS

Fluorimetric analyses of the ammonium fluorescein aerosol material were made with an Aminco-Bowman spectrophotofluorometer, with a xenon lamp (Catalog Numbers 4-8202 and 4-8202B). The unit was equipped with monochrometers for both exciting and emitted light. Instrument settings used in the analyses were as follows:

- Excitation wave length--482 nm
- Emission wave length--540 nm
- Primary slits--full open
- Secondary slits--5 mm
- Photomultiplier slit--0.1 mm
- Meter multiplier setting--to give transmittance reading between 30 and 90%
- Filter used--Corning 3-69 (to eliminate interferences with excitation wave length)

The transmittance of the ammonium fluorescein solutions followed Beers' Law at concentrations between 4×10^{-7} gm/cm^3 and 1×10^{-10} gm/cm^3. The fluorescence was markedly a function of pH, increasing by a factor of 25 as the pH was increased from 4 to 10. Samples were dissolved in a solution of ammonium hydroxide having an initial pH of 11.

Samples for analysis (1.5 to 2 cm^3) were placed in a clean, dry cuvette (fused quartz) of rectangular cross section.

It was found that a single washing of a Nuclepore filter was sufficient to remove the sample deposit. Therefore, filters were simply immersed and agitated in 10 cm^3 of the ammonium hydroxide solution having a pH of 11. If the resulting concentration of ammonium fluorescein was above the preferred range for analysis, the sample was diluted 10 to 1 with the ammonium hydroxide solution of pH 11.

Experience with replicated analyses indicated that the error in analysis did not exceed 1% except for the very smallest samples, for which the error was somewhat larger.

GENERAL TEST PROCEDURE

Scrubber performance tests were commonly made in groups, with the scrubber and aerosol generator being allowed to operate continuously between tests while the scrubber operating conditions were being changed. The aerosol generator commonly required a warm-up period of about 15-20 minutes before the aerosol output (observed in the glass spray trap) appeared visually to reach its maximum level. Except in a few exploratory tests, the generator was adjusted to give its maximum output.

In general, it was relatively easy to adjust the scrubber operating conditions except when it was desired to operate with the inlet gas near saturation with water vapor. When hot water was used in scrubbing, the water was frequently used on a once-through basis, with the temperature being adjusted by addition of steam at the ejector. However, control of the water temperature was somewhat more satisfactory when the water was recirculated and its temperature was adjusted at the holding tank.

Before the start of a test, the sampling filter holders were preheated, then inserted into the gas stream at the inlet and outlet of the scrubber and permitted to come up to temperature with the filter faces turned out of the gas stream. The holders were then turned to face the filters into the gas stream, and the gas flow was started and stopped simultaneously. Once the procedure was reduced to a routine, the sampling period was usually five minutes. During this period, the quantities of aerosol collected on the filters were mostly in the range of 0.1 to 15 μg, which could be analyzed with precision. Aerosol concentrations in the inlet gas to the scrubber ranged from about 0.2 to 0.8 μg/liter of dry air (25°C and 1 atm.), depending on the gas flow in the scrubber and on the generation rate. All gas samples were referred to the selected standard gas conditions: 25°C, 1 atm. pressure and the dry basis. The corresponding aerosol concentrations measured at the inlet and outlet of the scrubber were used to calculate the collection efficiency.

During the period of the sampling run, readings were made of the flowmeters and system temperatures and pressures.

Analyses of the ammonium fluorescein in the scrubbing water were apparently interfered with by residual chlorine from the water purification. Recirculating water through the scrubber with a flow of ambient air apparently stripped out the interfering chlorine. Hence, where some check runs were made at Ambient scrubbing conditions to determine material balances on the ammonium fluorescein, a supply of water that had been air-stripped to remove chlorine was first accumulated in the holding tank and then pumped through the scrubber in a single pass during the scrubbing tests.

Except in a few instances, no direct measurement was made of the water vapor content of the air at the outlet of the scrubber. If the gas was sampled for a sufficient period, the moisture content could be determined from the amount of condensate collected in the condenser. However, the standard sampling period was too short for collection of a volume of condensate that could be measured with reasonable precision. Hence, the outlet gas moisture content was calculated by assuming saturation at the outlet gas temperature if the outlet water temperature was equal to or greater than the outlet gas temperature; if the outlet water was colder than the outlet gas, the gas was assumed to have a water vapor partial pressure equal to the vapor pressure of the water at its outlet temperature. Allowance was made in the calculation for the total pressure (subatmospheric) at the outlet of the scrubber.

SECTION VII

RESULTS AND DISCUSSION

As soon as the experimental equipment had undergone a preliminary shakedown and appeared to be in suitable operating condition, a series of "screening" tests was made to provide a quick indication of the range of collection efficiencies that might be obtained under adiabatic saturation, condensing, and vaporizing conditions. The scrubber was operated at a single level of effective friction loss throughout the tests, although setting the other operating conditions made it necessary to use varying liquid-to-gas ratios in the different experiments. Two or three replicate tests were made at each operating condition. (The results are presented under the appropriate headings below.)

Although the aerosol generation rates observed during the tests varied by as much as ±35% of the mean value, the agreement between replicate tests was generally very good or excellent, and it therefore was considered that the variations in aerosol generator output probably did not coincide with any substantial variations in the particle size of the aerosol. However, it was recognized that such variations might take place. As additional data were obtained, difficulties in replicating results appeared, and strong evidence of variations in the aerosol particle size did emerge. Since the interpretation of scrubber performance at various conditions was dependent on constancy of the aerosol characteristics, it became necessary to devote a major effort to attempts to stabilize the generator operation (see Section VI) and characterize the aerosol. In the end, it was not actually found possible to prevent the variations in the aerosol characteristics. Nevertheless, the observation that these variations were correlated with the aerosol generation rate made it possible to select comparable collection efficiency data for different scrubber operating conditions, and thus to interpret the effect of the operating conditions on scrubber performance. However, it was necessary to obtain many more data to establish the correlations than was originally anticipated.

AEROSOL GENERATION AND CHARACTERIZATION

The measures taken in the effort to stabilize the performance of the aerosol generator (see Section VI) apparently had essentially no effect. There was a preliminary indication that raising the temperature of the liquid in the nebulizer to 35°C increased the aerosol generation rate. Later, it became evident that the generation varied over about the same, wide range whether the nebulizer was operated at 35°C or at ambient temperatures (about 25°C). Surveyed over a period of days, the generation rate appeared to follow no consistent or systematic trends. The rate showed apparently random short-term variations about the average value, and within periods of from several hours to a day or more, shifts in the average generation rate appeared.

After the aerosol generator was equipped to operate at 35°C, a series of scrubber efficiency tests was made at ambient operating conditions (see Table 2), all in the course of one day. Tests were made at a number of liquid and gas rates and gas pressure drops. All the aerosol generation rates were high, ranging from 1747 to 4097 μg/min., the latter value being the highest observed during the entire investigation. Never on any other occasion were the generation rates uniformly so high, nor were so many very high individual values observed. The collection efficiency data, studied in the relation to the effective friction loss, showed a wide scatter.

Table 2

SCRUBBER PERFORMANCE DATA FOR AMBIENT SCRUBBING TESTS
(Aerosol Generator Temperature 35°C)

Test Code No.	Aerosol Generation Rate (μg/min)	Contactor Orifice Size (cm)	Inlet Gas Flow Rate (std liters/min)	Gas Moisture Content (g/g dry air)		Gas Temperature (°C)		Water Temperature (°C)		Gas Velocity in Orifice[a] (m/sec)	Liquid-to-Gas Ratio $\left(\frac{\text{liters}}{\text{Sm}^3}\right)$	Effective Friction Loss (mm WC)	Collection Efficiency (%)	Transfer Units (N_t)
				In	Out	In	Out	In	Out					
EA														
6	1864	3.81	1140	0.01[b]	0.008	33.3	25.6	10.6	10.6	16.7	25.5	274	56.3	0.828
7	1747		1130		0.010	32[c]	27.8	14.4	15.0	16.5	42.8	535	69.7	1.19
8	1784		1130		0.013	32[c]	28.9	18.9	18.3	16.5	42.8	535	72.3	1.28
9	2743		1130		0.008	32[c]	26.1	11.7	11.7	16.5	57.2	810	90.63	2.37
10	2634		2110		0.008	32[c]	22.8	11.7	11.7	30.8	30.7	1480	96.95	3.49
11	1898		2120		0.008	29.4	22.2	10.6	10.6	31.0	19.1	870	88.9	2.20
12	1926		2110		0.008	38.9	22.2	11.1	11.1	30.8	9.53	304	65.6	1.07
13	1889		2110		0.009	32.8	23.3	11.1	12.2	30.8	5.40	272	52.1	0.736
14	2803		2940		0.010	31.1	26.7	13.9	15.0	43.0	1.29	259	65.2	1.06
15	4097		2770		0.009	31.7	23.3	13.3	12.2	40.5	2.05	279	78.3	1.53
16	2348		2770		0.008	32.2	22.8	11.7	11.7	40.5	5.60	535	82.9	1.77
17	1988		2770		0.008	30.6	22.2	11.7	11.7	40.5	5.52	535	76.5	1.45
18	2799		2770		0.008	30.6	21.1	11.1	10.6	40.5	10.3	810	92.01	2.53
19	2138		2770		0.008	30.6	20.6	10.6	10.6	40.5	16.9	1380	96.19	3.27
20	3444		3530		0.008	29.4	20.6	11.1	11.7	51.6	4.50	843	93.90	2.80
21	1749		3520		0.009	30.0	22.2	12.2	13.3	51.5	1.56	429	68.9	1.17
22	1783		3520		0.010	29.4	22.8	13.9	15.0	51.5	0.699	325	57.3	0.851

[a] Calculated at standard gas conditions.

[b] Estimated.

[c] Estimated. Inlet scrubbing water apparently splashed on thermometer.

The scrubber system was then used to study changes in the aerosol. The scrubber was operated on ambient air at a fixed set of conditions--air rate, water rate, and gas pressure drop. Repeated determinations were made of the collection efficiency, with the aerosol generator operated at ambient temperatures and at 35°C (see Table 3). The measured aerosol generation rates ranged from 662 to 1705 μg/min., and the collection efficiencies from 67.3 to 77.5% (1.12 to 1.49 transfer units). The plot of transfer units vs. aerosol generation rate (Figure 3) suggested a trend to increasing collection efficiency with increase in the aerosol generation rate, which inferred that the increase in the generation rate coincided with an increase in the average particle size of the aerosol.

The data shown in Figure 3, together with other observations in the same period, indicated that operating the generator at 35°C neither stabilized its output nor clearly increased the output above that obtained during operation at ambient temperature. Therefore, use of the higher temperature was abandoned, and all subsequent operation of the generator was carried on at ambient temperatures.

Subsequent studies of scrubber performance at various operating conditions (see below) developed additional strong evidence that the variations in aerosol generation rate did coincide with changes in the average particle size of the aerosol, and possibly--if not probably--in the particle-size distribution as well. With the aid of this background, the data from the early tests (Table 2) were re-examined and plotted in groups according to relatively narrow ranges of aerosol generation rate (see Figure 4). When treated in this manner, the data show correlations that are actually quite striking in their excellence and are in agreement with earlier experience that indicated that scrubber performance data for a consistent aerosol can yield very close correlations. The performance curves for the generation rates of 1864-2138 and 2348-2803 μg/min are generally consistent with the trends in the performance data later obtained

Table 3

SCRUBBER PERFORMANCE DATA FOR AMBIENT SCRUBBING TESTS AT FIXED SCRUBBER OPERATING CONDITIONS[a]

Test Group No.	Test Code No. EA	Aerosol Generator Temperature (°C)	Aerosol Generation Rate (μg/min)	Collection Efficiency (%)	Transfer Units (N_t)
1	26	Ambient	710	70.4	1.22
	27		662	67.3	1.12
	28		688	67.5	1.12
	29		715	68.4	1.15
2	30	35	1041	69.5	1.19
	31		1024	68.9	1.17
	32		1051	69.3	1.18
	33		1029	69.3	1.18
3	34	35	1149	69.9	1.20
	35		1168	70.4	1.22
4	36	Ambient	1002	70.9	1.24
	37		1023	70.2	1.21
	38		1044	68.8	1.17
	39		1276	74.6	1.37
5	40	Ambient	1178	77.5	1.49
	41		1136	72.5	1.29
	42		1085	71.5	1.25
	43		1128	71.9	1.27
6	44	35	1462	71.8	1.27
	45		1705	77.0	1.47
	46		1521	74.0	1.35
	47		1514	73.9	1.35

[a] Contactor orifice diameter = 3.81 cm.
Gas rate = 2800 std. liters/min.
Water rate = 15.1 liters/min.
Liquid-to-gas ratio = 5.39 liters/Sm^3.
Effective friction loss = 520 mm WC.

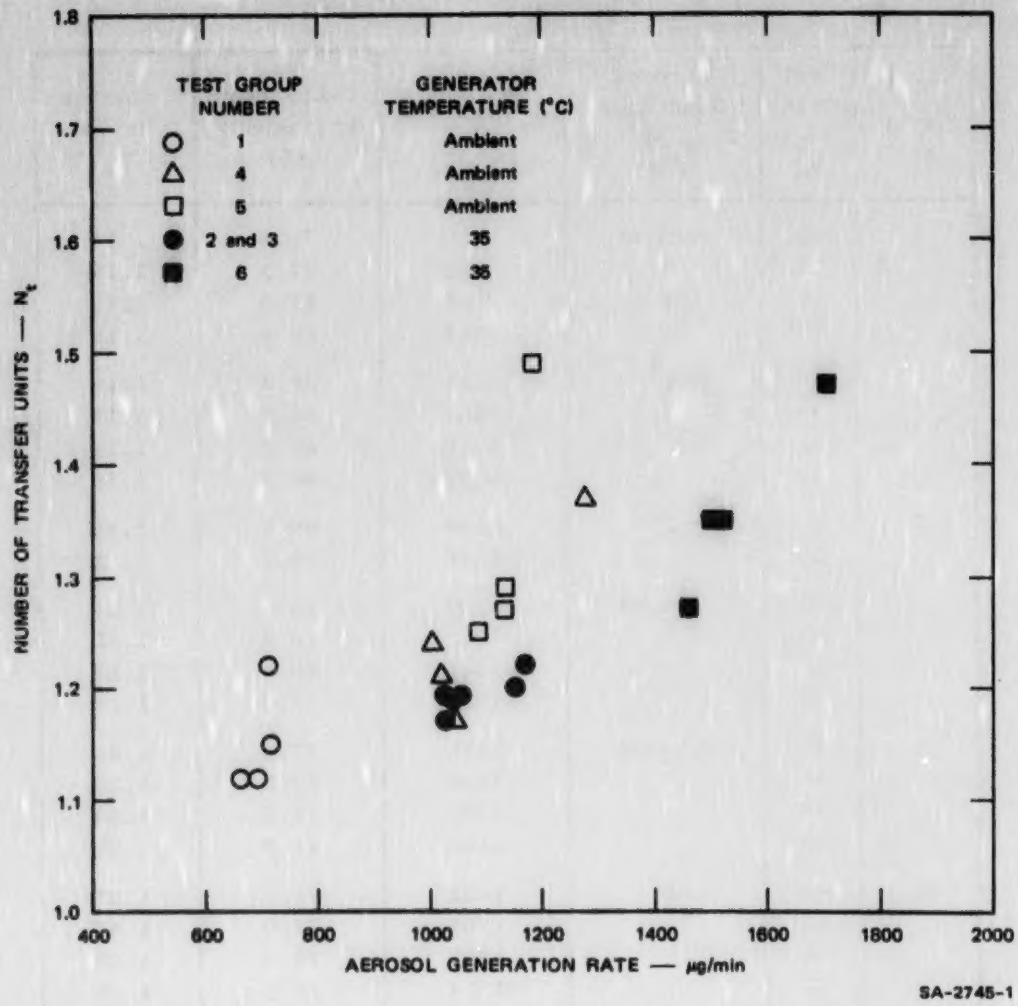


FIGURE 3 SCRUBBER PERFORMANCE AT FIXED OPERATING CONDITIONS (Tests EA-26 through EA-47)

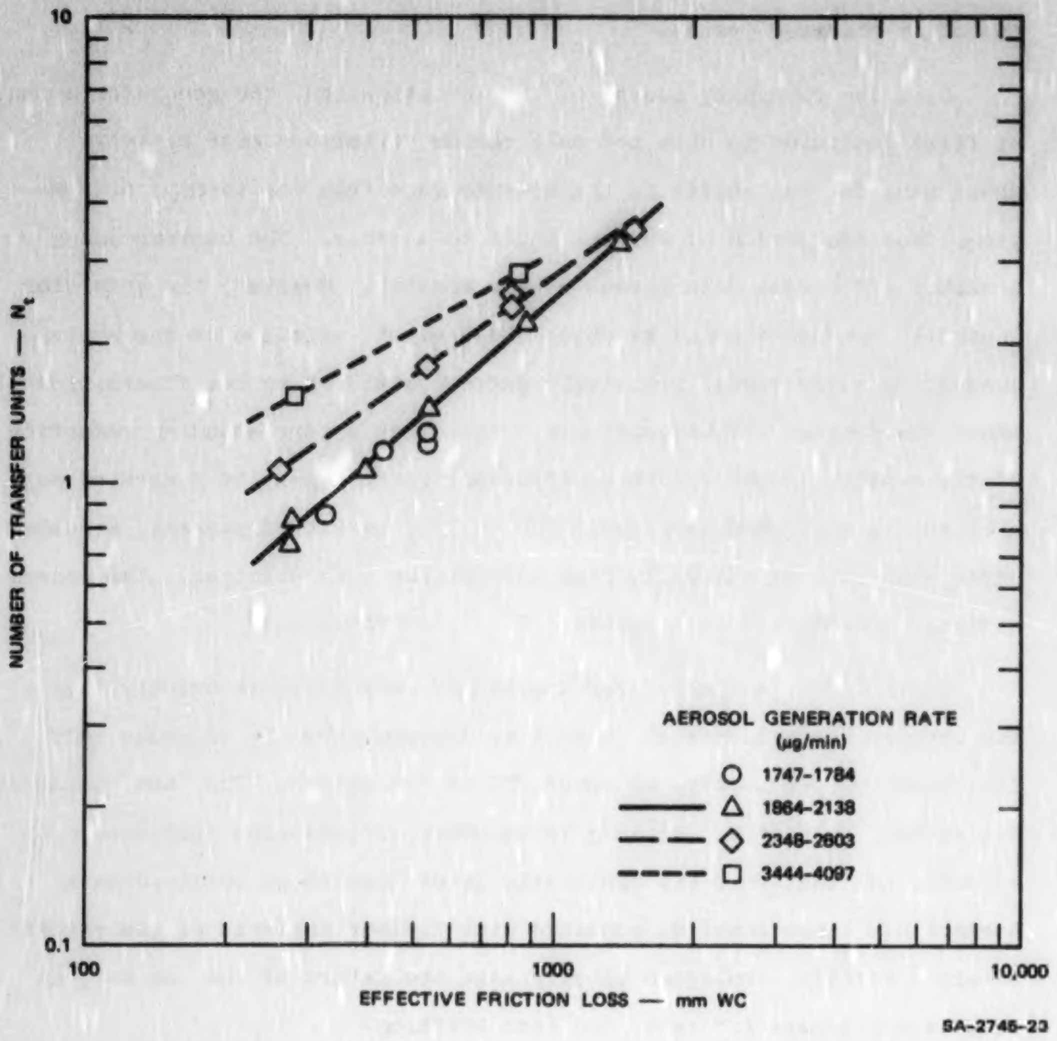


FIGURE 4 SCRUBBER PERFORMANCE CURVES FOR AMBIENT SCRUBBING TESTS EA-6 THROUGH EA-22
(Aerosol generator at 35°C)

in ambient scrubbing tests with lower aerosol generation rates. Since only two data points were obtained in the range 3444-4097 μg/min, the performance curve they yield is merely indicative, but is consistent with the other observed trends.

Over the remaining course of the investigation, the generator output at first continued to show not only random variations over relatively short periods, but shifts in the average rate from day to day, or sometimes from one period of several hours to another. The corresponding scrubber efficiency data showed a wide scatter. However, the generator gradually reached a point at which the band of variation of the average generation rates became relatively narrow, although random fluctuations about the average values continued. There was a corresponding reduction of the scatter in the scrubber efficiency data. When the generator settled into a mode producing about 750 to 1100 μg/min of aerosol, scrubber efficiency data of generally high consistency were obtained. The corresponding aerosol is termed "Aerosol A" for convenience.

Still later, the nebulizer apparently malfunctioned briefly, and the aerosol generation rate thereafter dropped abruptly to about half that observed previously, or about 350 to 700 μg/min. The "new" aerosol, designated "Aerosol B," again gave scrubber efficiencies that were consistent, but that were systematically lower than those obtained with Aerosol A. These results, combined with further analysis of the results obtained earlier, indicated clearly that the nature of the aerosol, as well as the generation rate, had been shifting.

Some additional observations, made with Institute support since termination of this experimental program, indicated a continuing drop in the average aerosol generation rate. It appears likely that this behavior was associated with deterioration of the transducer, or aging of the transducer crystal, of the nebulizer. Replacement of the transducer restored the aerosol generation rate to the previous "normal" range of about 900 to 1300 μg/min.

AMBIENT SCRUBBING TESTS

The tests of scrubbing ambient air with ambient water had two major objectives:

(1) to establish the contacting power/efficiency relationship for the test aerosol in the absence of appreciable condensation or evaporation of water

(2) To determine the degree to which liquid-to-gas ratio might have an influence on collection efficiency, independent of the contacting power.

Scrubbing at ambient temperatures involves only small absolute changes in the humidities of the air. Strictly, the attainment of "neutral" conditions with respect to vaporization and condensation phenomena requires that saturated gas should be scrubbed with water at the same temperature. In practice, this is experimentally difficult to carry out without the danger of bringing in other, undesired phenomena. If the incoming gas stream is saturated, even a small temperature drop may result in some condensation of water vapor and possible growth of the test aerosol upstream of the gas/liquid contacting section, with consequent changes in the contacting power/efficiency relationship.

Attempts to make neutral tests at 54°C and 74°C were made during the initial series of "screening" tests. The inlet gases were actually brought in at temperatures several degrees above the saturation temperature to avoid the possibilities of premature condensation. For those few "neutral" tests that were not actually abortive, the efficiencies obtained were in the same range as those obtained at adiabatic saturation and other operating conditions, but presented no consistent, interpretable picture. In retrospect, it appears that the results reflected variations in the aerosol, which were not fully appreciated at the time. Ambient scrubbing gave results that were at least similar to those obtained with adiabatic saturation scrubbing with a comparable aerosol. There was no clear indication that temperature as such had any appreciable effect on scrubber performance over the range of about 25-80°C in which most of the scrubbing action presumably took place under the various scrubbing test conditions.

Had the liquid-to-gas ratio been found to have independent effects on scrubber efficiency, it would have made interpretation of test results especially difficult, since securing different amounts of condensation involved use of different liquid-to-gas ratios. The first ambient scrubbing tests were made systematically to display the effects of orifice contactor size, orifice gas velocity, and liquid-to-gas ratio (see Table 4). The evidence of aerosol particle-size variations (previously discussed) appeared speedily in the form of a wide scatter in the collection efficiency data (see Figure 5). Although the data points showed a general correlation of transfer units with effective function loss, the straight-line relationship suggested by previous experience was not in evidence. However, there was no indication--within the uncertainty posed by the scatter in the data--that there were independent effects of gas velocity or liquid-to-gas ratio on the number of transfer units.

When evidence mounted that the apparent variations in aerosol particle size were not purely random, but were correlated with the aerosol generation rate, the ambient scrubbing data of Table 4 were grouped according to convenient ranges of aerosol generation rate and replotted (Figures 6 through 10). (The correlation curves from Figures 6-10 are presented together without data points in Figure 11, for purposes of comparison.) The ranges of generation rate were chosen on a largely arbitrary basis, and slightly different choices might produce somewhat better correlations. Nevertheless, it is evident that the data are generally quite well rationalized by this device. The poorest correlation is given by the data for

Table 4

SCRUBBER PERFORMANCE DATA FOR AMBIENT SCRUBBING TESTS

Test Code No.	Aerosol Generation Rate (μg/min)	Contactor Orifice Size (cm)	Inlet Gas Flow Rate (std liters/min)	Gas Moisture Content (g/g dry air)		Gas Temperature (°C)		Water Temperature (°C)		Gas Velocity in Orifice (m/sec)	Liquid-to-Gas Ratio $\left(\frac{\text{liters}}{\text{Sm}^3}\right)$	Effective Friction Loss (mm WC)	Collection Efficiency (%)	Transfer Units (N_t)
				In	Out	In	Out	In	Out					
EA														
48	1370	3.81	1230	0.009	0.008	33.3	25.6	11.7	11.1	18.0	18.7	228	44.3	0.585
49	1366				0.008	31.1	25.6	11.1	11.1		26.8	345	57.1	0.846
50	1503				0.008	32[b]	25.0	11.1	11.1		36.6	516	72.9	1.30
51	1497				0.008	32[b]	25.6	12.8	12.2		52.8	833	85.6	1.94
52	1396		1740	0.009	0.009	31[b]	25.0	12.2	12.2	25.4	37.4	1217	93.7	2.77
53	846				0.008	31[b]	23.3	11.1	11.1		25.9	787	78.4	1.53
54	1358				0.008	31.1	23.3	11.1	11.1		19.0	516	72.7	1.30
55	1292				0.009	32.2	26.1	11.7	11.7		8.62	239	40.3	0.515
56	1280		2650	0.010	0.010	35.0	27.2	16.7	14.4	38.7	1.43	191	35.6	0.441
57	1687				0.009	31.7	22.8	11.7	11.7		5.66	442	77.7	1.50
58	1148				0.008	26.7	21.1	11.1	10.6		12.5	864	88.1	2.13
59	1179				0.008	26.1	20.6	10.6	10.6		17.0	1176	93.5	2.74
60	1569		3640	0.010	0.012	27.8	23.9	18.3	16.7	53.2	0.52	282	60.9	0.940
61	1397				0.010	27.8	22.8	16.7	14.4		1.04	345	67.5	1.12
62	1503				0.009	27.8	20.0	11.1	11.7		4.12	767	88.9	2.20
63	1642				0.008	26.7	19.4	11.1	11.1		9.07	965	93.1	2.67
64	1440		1790	0.008	0.008	25.6	22.2	10.6	10.6	26.2	25.3	802	86.7	2.02
65	1234		2640		0.008	23.9	20.6	10.6	11.1	38.6	12.4	870	86.9	2.20
66	1063		3580		0.009	25.6	20.6	11.1	12.2	52.6	2.63	517	74.1	1.35
67	1316		2650	0.010	0.010	27.8	23.9	13.3	14.4	38.7	1.43	191	60.3	0.923
68	857		1390		0.009	31.1	23.9	11.7	11.7	20.3	10.9	151	12.0	0.304
69	885		1770		0.009	30.6	23.3	11.7	11.7	25.9	8.6	223	36.9	0.458
70	1771	2.54	850	0.010	0.008	27.8	26.1	11.1	11.1	28.0	38.8	1092	95.7	3.14
71	1029		864		0.008	28[b]	25.0	11.1	11.1	28.4	53.2	1707	97.2	3.57
72	1115		1220	0.010	0.008	29[b]	23.9	11.1	11.1	40.5	37.1	2680	99.24	4.88
73	1080				0.008	28.9	23.3	11.1	11.1	41.0	26.8	1722	97.4	3.66
74	1004				0.009	34.4	23.9	11.7	11.7	40.8	15.7	963	90.7	2.37
75	978		1770	0.010	0.008	32.2	23.3	11.1	11.1	58.2	14.8	2300	98.7	4.31
76	1008				0.009	31.7	22.8	11.7	11.7		8.47	1247	94.3	2.87
77	1317		2390	0.010	0.010	30.0	22.8	12.8	14.4	78.7	1.59	1087	94.1	2.83

Table 4 (Continued)

Test Code No.	Aerosol Generation Rate (μg/min)	Contactor Orifice Size (cm)	Inlet Gas Flow Rate (std liters/min)	Gas Moisture Content (g/g dry air)		Gas Temperature (°C)		Water Temperature (°C)		Gas Velocity in Orifice (m/sec)	Liquid-to-Gas Ratio $\left(\frac{\text{liters}}{\text{Sm}^3}\right)$	Effective Friction Loss (mm WC)	Collection Efficiency (%)	Transfer Units (N_t)
				In	Out	In	Out	In	Out					
EA														
78	860	3.81	3640	0.01[c]	0.012	33.9	29.4	17.8	16.7	53.3	0.519	302	45.7	0.611
79	1053		2648		0.009	30.0	24.4	16.1	12.8	38.7	1.43	200	29.1	0.344
80	1160		1770		0.008	31.1	23.3	11.7	11.1	25.9	8.53	217	34.5	0.423
81	1150		1230	0.01[c]	0.008	33.3	23.9	11.1	10.6	18.0	18.9	217	34.6	0.424
82	1146				0.008	33.9	23.9	11.1	10.6				33.9	0.414
83	1159				0.008	32.8	24.4	10.6	10.6				39.2	0.497
84	976	2.54	1770	0.01[c]	0.009	37.2	22.8	11.7	12.2	58.2	8.54	1290	96.20	3.27
85	1487				0.009	30.0	21.1	11.1	11.7		9.18	1413	97.75	3.79
86	1165				0.008	30.0	21.1	11.1	11.1		10.9	1633	97.86	3.84
87	1176				0.008	29.4	21.1	11.1	11.1		12.8	2000	98.74	4.38
88	1212		1240	0.01[c]	0.008	25.0	22.2	10.6	10.6	45.8	35.5	2532	99.45	5.18
89	1243				0.008	25.0	22.2	10.6	10.6		26.1	1768	98.27	4.06
90	1278				0.008	25.0	22.2	10.6	10.6		18.3	1224	95.81	3.17
91	525[d]				0.008	25.0	22.2	10.6	10.6		18.3	1224	95.90	3.19
92	1866		1150	0.01[c]	0.028	32.2	32.2	30.6	30.6	37.8	39.3	2590	99.54	5.38
93	1795		1075		0.032	33.3	33.9	33.3	32.8	35.4	24.6	1237	96.52	3.36
94	1585		1150		0.036	36.7	35.0	35.6	34.4	37.8	12.9	663	87.3	2.06
95	1817		1135		0.04	36.7	34.4	36.7	--	37.2	3.51	292	58.7	0.883
96	1675		770		0.043	39.4	36.1	38.9	37.8	25.3	9.83	209	42.8	0.559
97	1674		2110		0.043	39.4	37.8	41.7	37.8	69.5	7.27	1854	98.48	4.19
98	1044		806	0.01[c]	0.017	32[b]	26.1	21.1	22.2	26.5	80.3	2946	99.49	5.27
99	984		1115		0.008	32[b]	23.3	11.1	11.1	36.7	43.4	2642	99.06	4.67
100	1021		1530		0.008	25.6	21.1	11.1	11.1	50.3	21.2	2291	98.44	4.16
101	937		2036		0.009	30.0	20.0	11.1	11.7	67.0	9.53	1902	97.25	3.59
102	847		1153	0.01[c]	0.014	32.8	25.6	19.4	19.4	37.9	13.1	673	83.5	1.80
103	965		1153		0.020	32[b]	27.8	23.9	23.9	37.9	39.3	2565	99.27	4.92
104	967		789		0.024	36.1	30.6	28.3	27.8	26.0	9.59	224	40.1	0.512
105	973		1153		0.026	36.1	31.1	31.1	28.9	37.9	3.29	272	48.0	0.654
106	1052		1153		0.036	33.3	34.4	35.0	34.4	37.9	22.5	1250	93.6	2.75
107	797	4.45	1924	0.01[c]	0.009	28.9	23.9	12.8	12.8	20.7	3.93	82.1	11.5	0.123
108	789		2506		0.010	28.9	23.9	12.8	13.3	26.9	3.02	136	16.1	0.175
109	766		2741		0.010	28.9	23.3	12.8	13.3	29.4	2.76	162	17.1	0.187

Table 4 (Concluded)

Test Code No.	Aerosol Generation Rate (μg/min)	Contactor Orifice Size (cm)	Inlet Gas Flow Rate (std liters/min)	Gas Moisture Content (g/g dry air)		Gas Temperature (°C)		Water Temperature (°C)		Gas Velocity in Orifice (m/sec)	Liquid-to-Gas Ratio $\left(\frac{\text{liters}}{\text{Sm}^3}\right)$	Effective Friction Loss (mm WC)	Collection Efficiency (%)	Transfer Units (N_t)
				In	Out	In	Out	In	Out					
EA														
110	765	2.54	548	0.01[c]	0.009	38.9	26.1	12.2	12.8	18.0	10.4	81.3	17.8	0.196
111	762		607		0.009	40.0	26.1	12.2	12.8	19.9	9.36	97.7	11.6	0.123
112	784		767		0.010	39.4	26.1	12.8	13.3	25.2	7.41	137	17.8	0.196
113	766		789		0.010	38.9	26.1	12.8	13.3	26.0	7.20	161	21.7	0.244
114	789	3.81	1479	0.01[c]	0.010	32.8	26.1	12.8	13.3	21.6	3.84	77.8	6.2	0.064
115	831		1712		0.010	32.2	26.1	12.8	13.3	25.0	3.32	103	12.0	0.127
116	868		1967		0.010	32.2	26.1	12.8	13.3	28.8	2.89	130	16.7	0.180
117	824		2235		0.010	31.7	26.1	12.8	13.3	32.7	2.54	164	22.9	0.260
118	374		2031	0.01[c]	0.010	28.9	24.4	13.9	14.4	29.7	1.87	115	6.5	0.067
119	355		2031		0.010	28.9	24.4	--	13.3	29.7	5.59	216	21.7	0.244
120	404		2031		0.010	28.3	22.2	12.8	13.3	29.7	8.29	293	33.4	0.406
121	421		2036		0.009	27.2	21.7	12.8	12.8	29.8	11.8	444	52.1	0.736
122	443		2025		0.009	25.0	21.7	12.2	12.2	29.6	16.0	588	62.5	0.982
123	398		3294		0.010	27.2	21.1	12.8	13.3	48.1	4.54	572	64.0	1.02
124	553	2.54	1150	0.006	0.009	31.1	23.3	12.8	12.8	37.8	16.9	897	85.5	1.93
125	541		1150		0.009	31.7	23.3	12.8	12.8	37.8	22.5	1271	91.60	2.48
126	548		1153		0.009	25.0	23.3	12.2	12.2	37.9	28.1	1587	94.82	2.96
127	565		1153		0.009	27[b]	23.9	12.2	12.2	37.9	38.2	2440	98.25	4.04
128	510		2111		0.010	29.4	22.8	13.3	13.3	69.4	1.80	866	84.8	1.88

[a] Calculated at standard gas conditions.

[b] Estimated. Inlet water apparently splashed on thermometer.

[c] Estimated.

[d] Generator output deliberately attenuated.

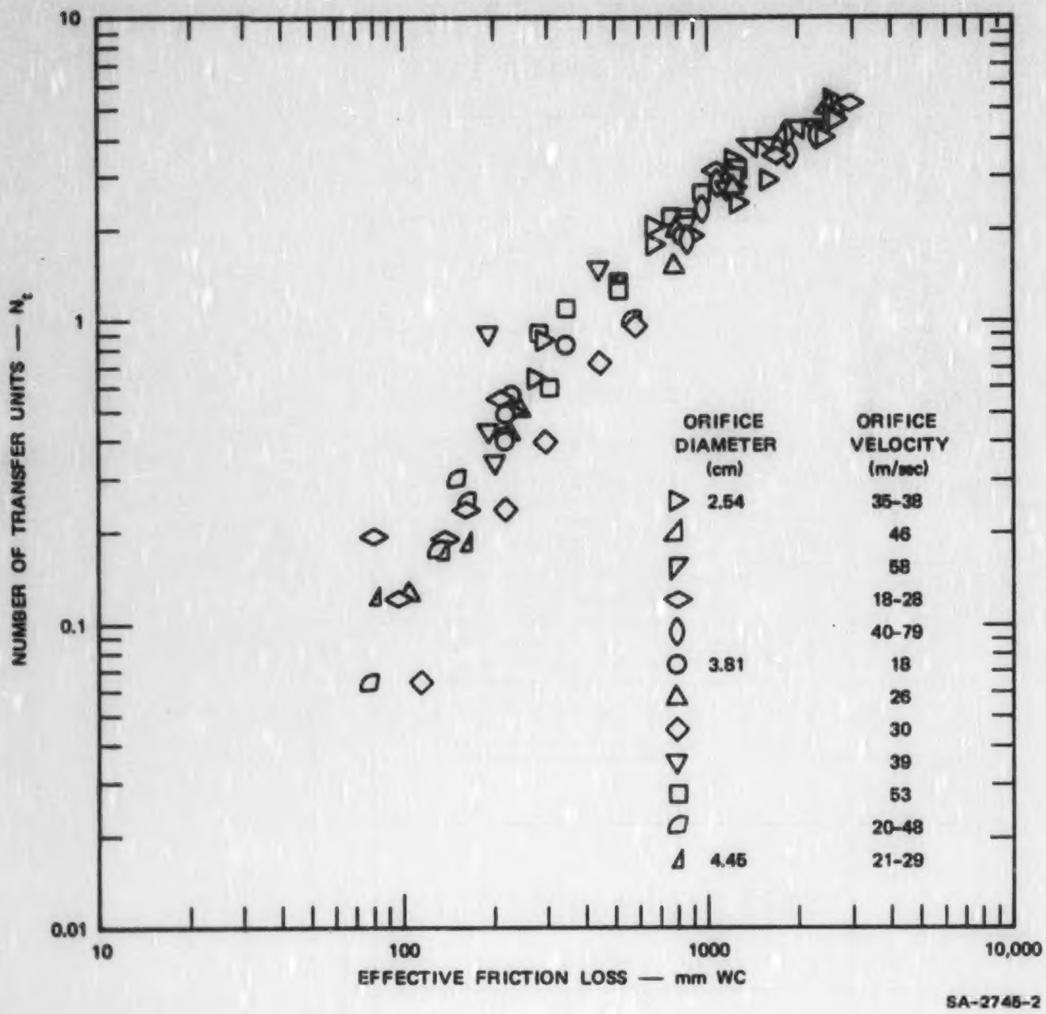
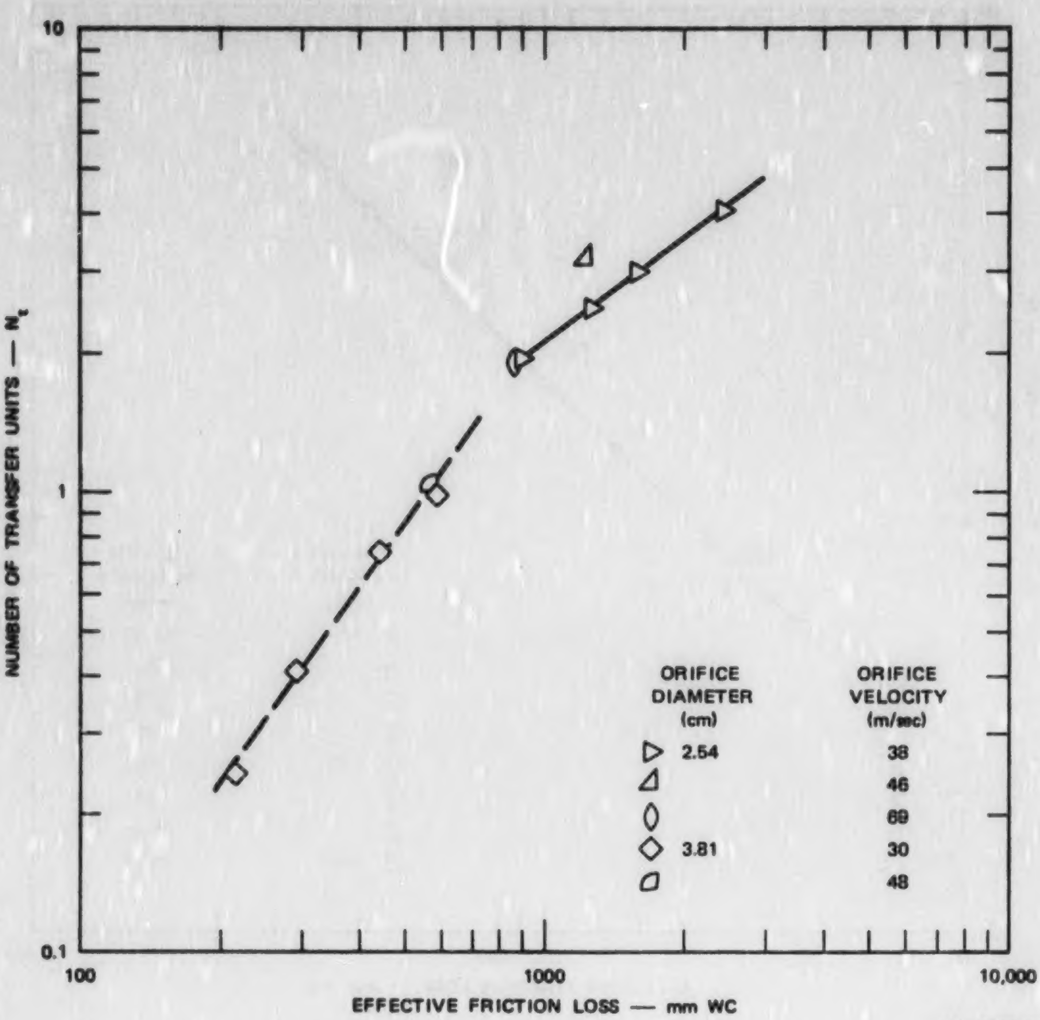
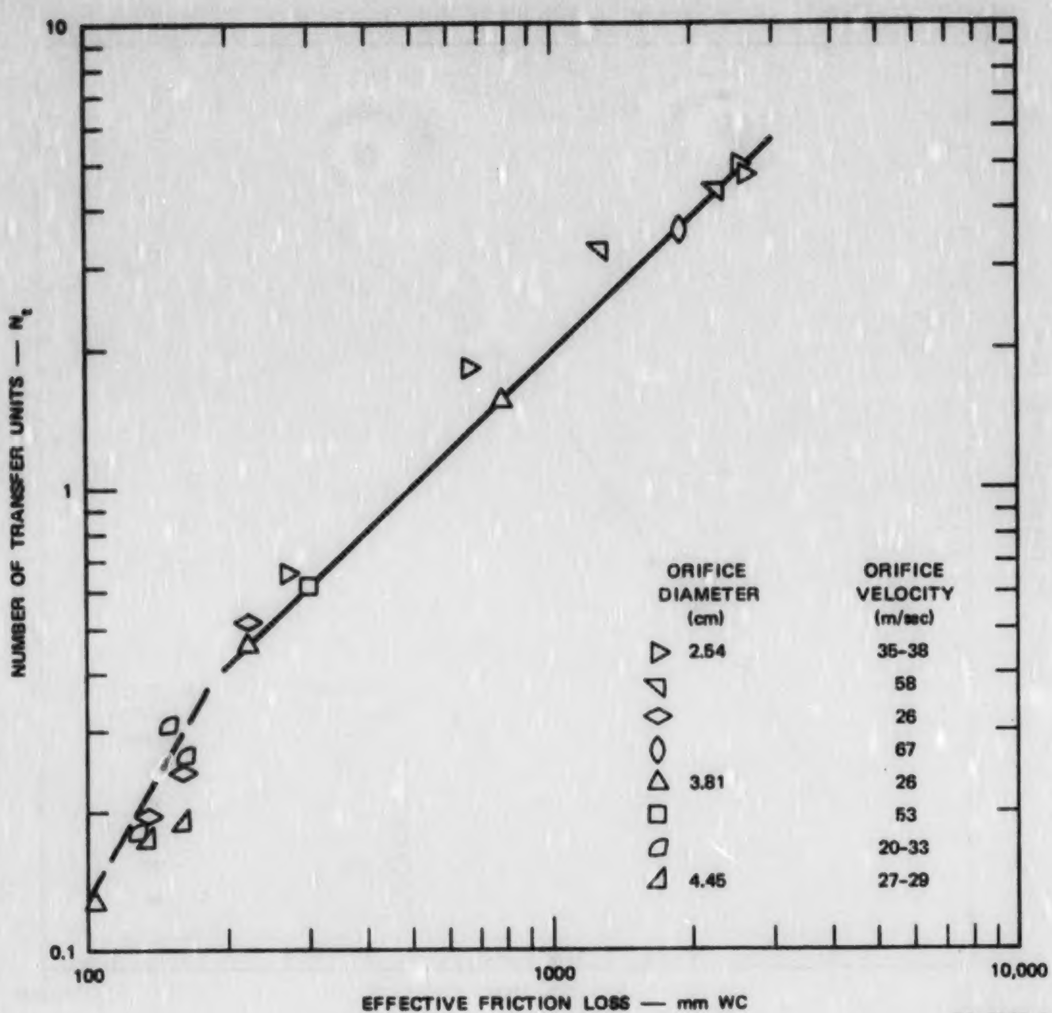


FIGURE 5 SCRUBBER PERFORMANCE DATA FOR AMBIENT SCRUBBING TESTS EA-48 THROUGH EA-128



SA-2745-3

FIGURE 6 SCRUBBER PERFORMANCE CURVE FOR AMBIENT SCRUBBING TESTS
Aerosol generation rates 350-570 μg/min.



SA-2745-4

FIGURE 7 SCRUBBER PERFORMANCE CURVE FOR AMBIENT SCRUBBING TESTS
Aerosol generation rates 750-1000 μg/min.

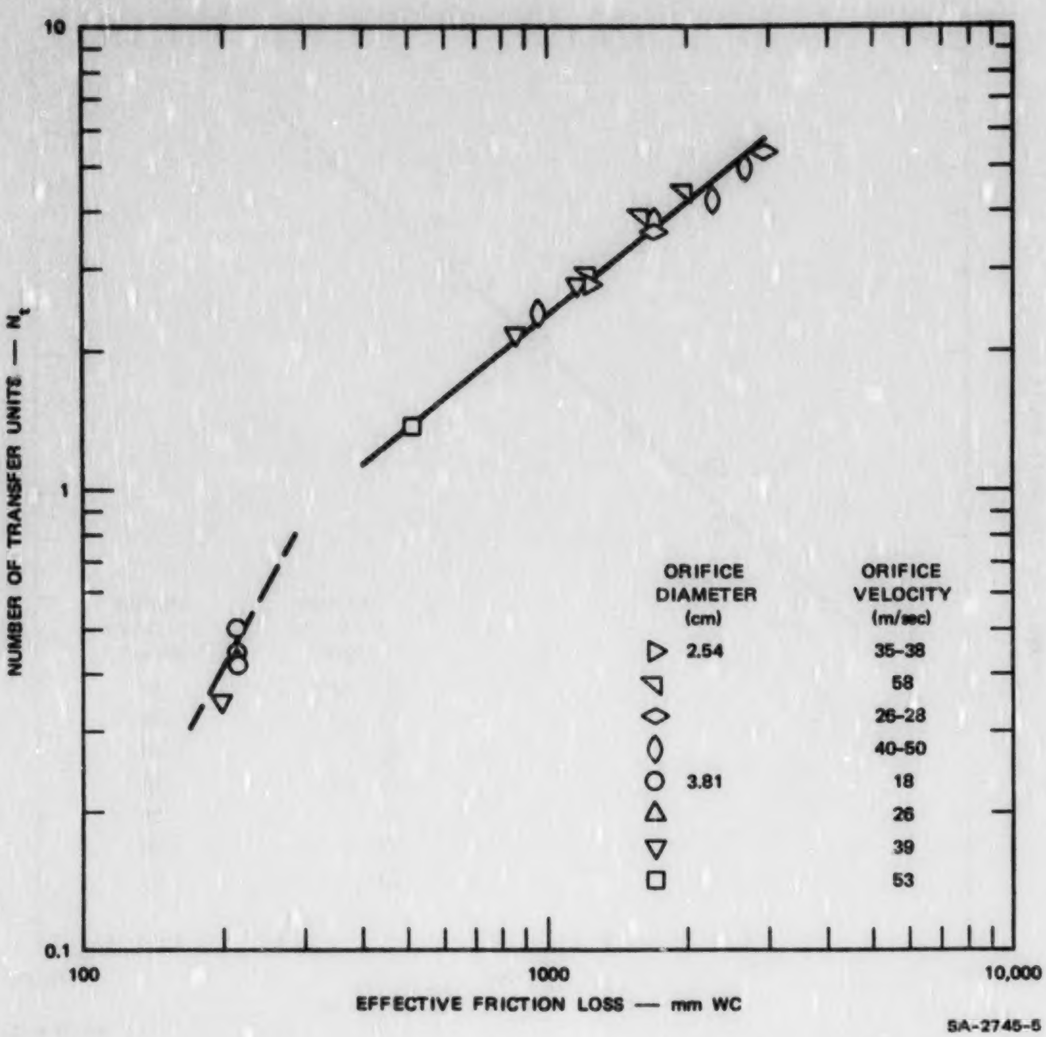


FIGURE 8 SCRUBBER PERFORMANCE CURVE FOR AMBIENT SCRUBBING TESTS
Aerosol generation rates 1000-1200 μg/min.

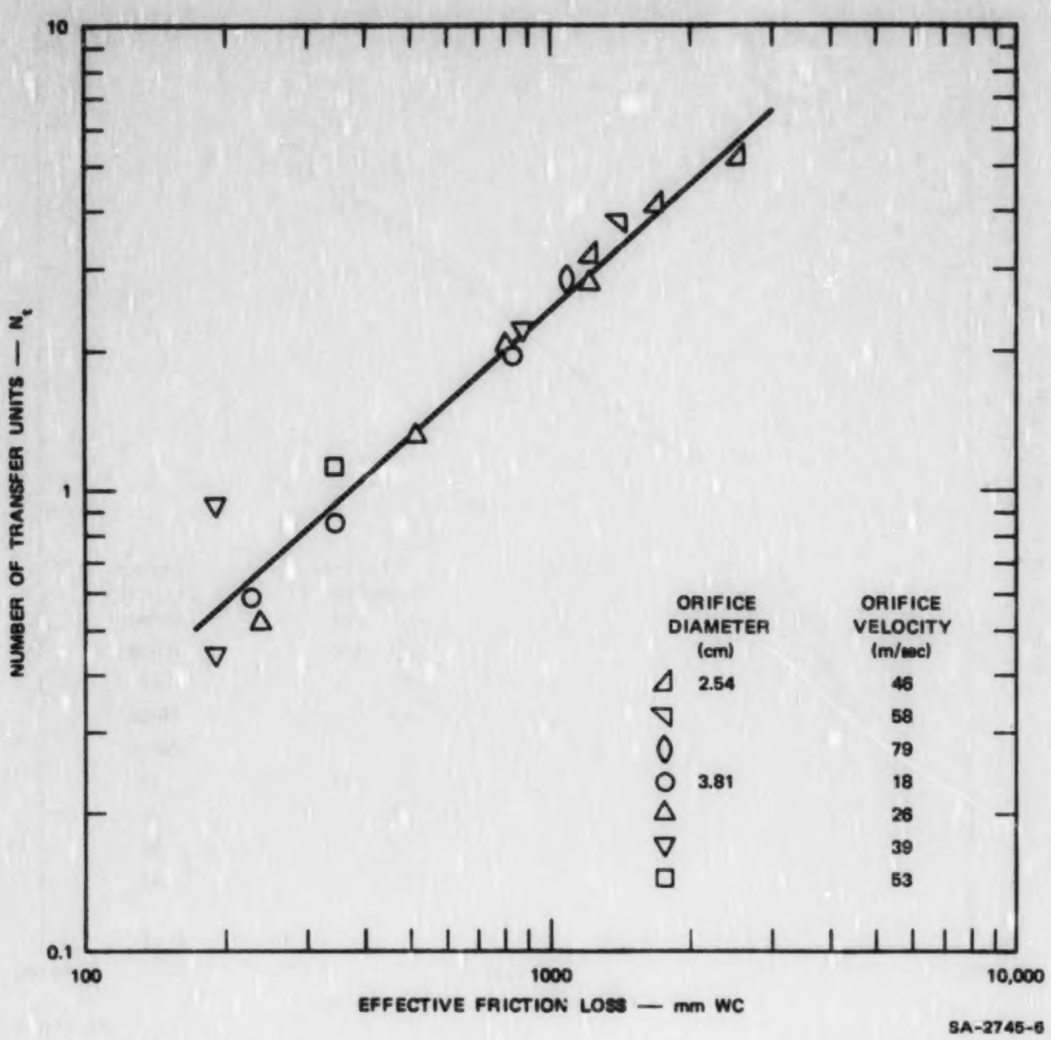


FIGURE 9 SCRUBBER PERFORMANCE CURVE FOR AMBIENT SCRUBBING TESTS
Aerosol generation rates 1200–1500 μg/min.

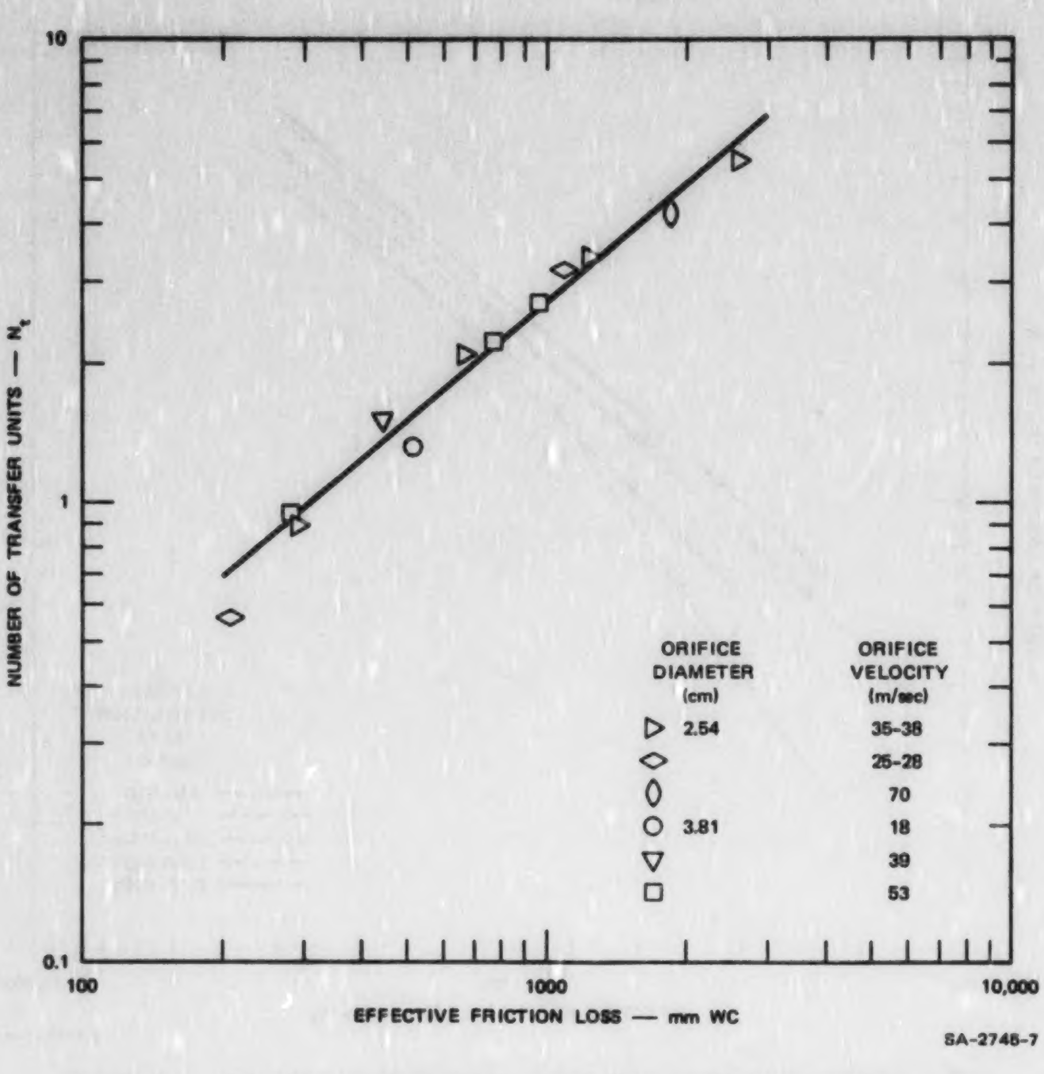


FIGURE 10 SCRUBBER PERFORMANCE CURVE FOR AMBIENT SCRUBBING TESTS
Aerosol generation rates 1500-1900 μg/min.

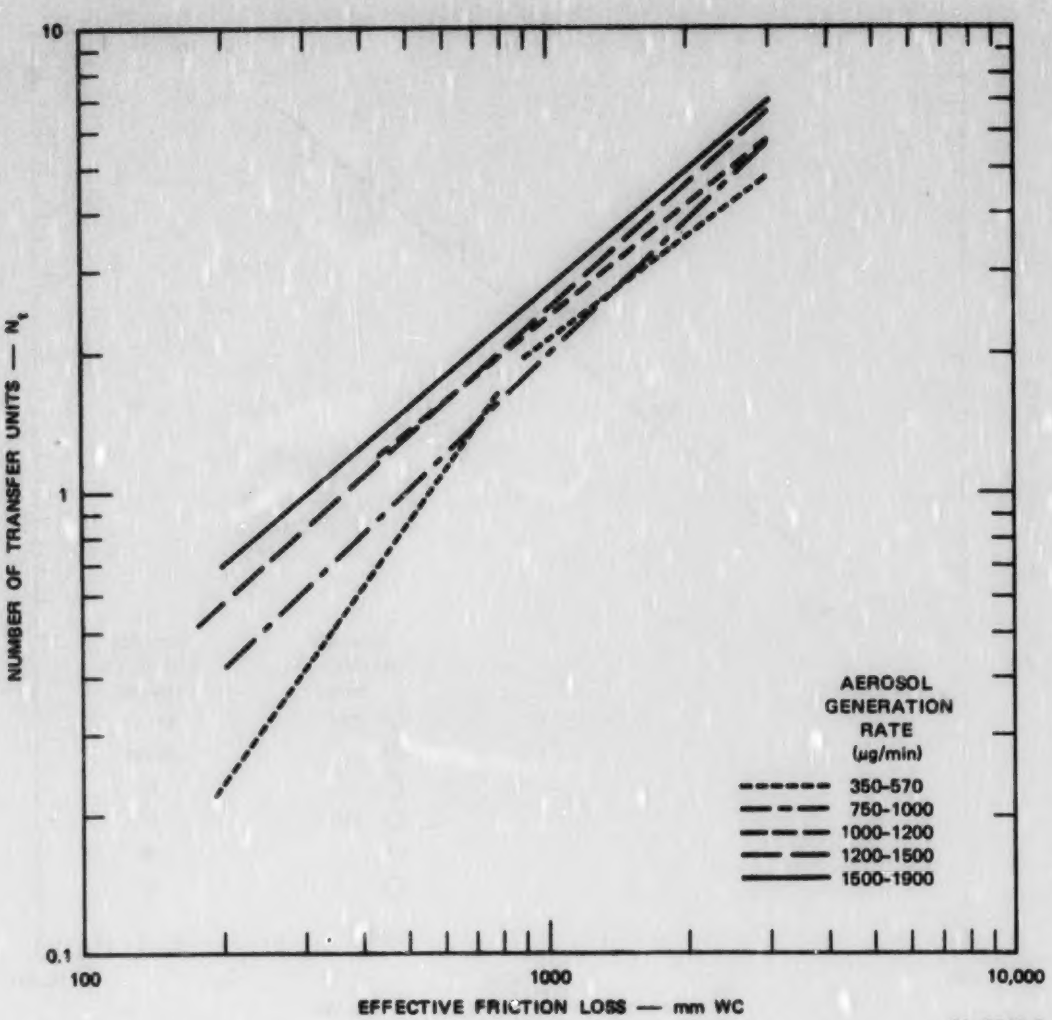


FIGURE 11 SUMMARY OF SCRUBBER PERFORMANCE CURVES FOR AMBIENT SCRUBBING TESTS

the generation rate of 750-1000 μg/min (Figure 7), which most nearly corresponds to the range producing the aerosol defined as "Aerosol A." The data of Figure 6, which were actually the last obtained (except for one point) were taken from tests with "Aerosol B." The one point from Test No. EA-91 was obtained by deliberately attenuating the output of the nebulizer at a time when it was producing about 1200 μg/min of aerosol at full power (Table 4). The efficiency for that run checked very closely the efficiency obtained in Test EA-90, made at the same conditions except with full generator output.

In Figures 6-10, the straight-line relationship of transfer units to effective friction loss (in a log-log plot) appears as suggested by experience in earlier investigations. However, another phenomenon, not previously observed, also appeared in Figures 6, 7, and 8. This was the appearance of a sharp drop-off of transfer units at low values of effective friction loss. It appears that in this region there is an essentially separate correlation of transfer units and effective friction loss (see Figure 6) that may give a second straight line with a slope exceeding unity. In Figures 7 and 8, the data in the low-efficiency region are too few and too imprecise to establish clear correlations.

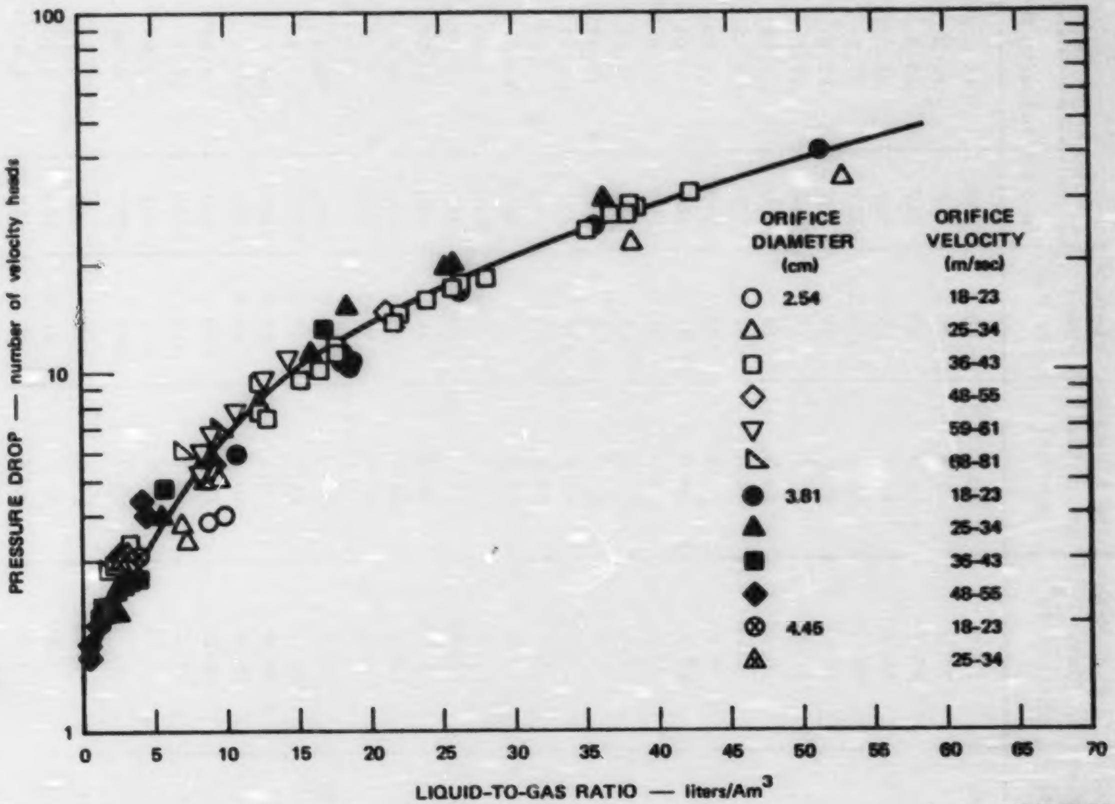
The correlations of Figures 6-10, as well as the other data correlations obtained during the investigation, demonstrate clearly that the relationship of transfer units to effective friction loss for the orifice scrubber was independent of gas velocity, liquid-to-gas ratio, and contactor orifice size, at least over the range of importance (See Appendix B). There may be exceptions in the cases where separate data correlations appear in the regions of low transfer units and low effective friction losses. However, in the principal operating range, orifice velocities were varied from 18 to 79 m/sec (59 to 259 ft/sec) and liquid-to-gas ratio from 0.52 to 80 liters/Sm^3 (3.9 to 600 gal/1000 Sft^3) without showing independent influences on collection efficiency. Few data were taken at liquid-to-gas ratios under 2 liters/Sm^3 (15 gal/1000 Sft^3), even in tests at low effective friction losses.

A correlation of the scrubber pressure drop data taken during the ambient scrubbing tests is shown in Figure 12. The pressure drop is expressed as the number of velocity heads based on the gas velocity through the contactor orifice (without allowance for the presence of the water), and is presented as a function of the liquid-to-gas ratio expressed in liters/Am^3. In this correlation, the gas volumes, velocities, and densities were computed at the measured scrubber inlet temperature and a pressure of one atmosphere (see Table 5). Since the pressure drop measured was the total across the contactor orifice, the mitre elbow ahead of the cyclone, and the cyclone itself, deviations were to be expected between results obtained at different orifice sizes and gas flow rates. The correlation curve is no more than a rough average for the data as presented.

ADIABATIC SATURATION TESTS

The Adiabatic Saturation tests were started, fortuitously, at a time when the aerosol generator first reached a relatively stable operating mode. Most of the data (see Table 6) can therefore be considered appropriate to Aerosol A. A few additional tests (No. AS-23 to AS-27) were taken after the generator reached its second stable mode and are generally appropriate to Aerosol B. The tests No. EN-2 to EN-4 were part of the series of preliminary screening tests.

The greater stability of the aerosol generator during these testing periods was reflected in the close correlation of the number of transfer units with the effective friction loss (Figures 13 and 14); the characteristic straight-line relationship was clearly defined. However, the tests with Aerosol A and Aerosol B each yielded a separate curve, with Aerosol B showing systematically lower collection efficiencies. Once again, gas



SA-2746-21

FIGURE 12 CORRELATION OF SCRUBBER PRESSURE DROP DATA FOR AMBIENT SCRUBBING CONDITIONS

Table 5

SCRUBBER PRESSURE DROP DATA FOR AMBIENT SCRUBBING TESTS

Test Code No. EA	Orifice Diameter (cm)	Liquid-to-Gas Ratio (liters/Am^3)	Gas Velocity in orifice[a] (m/sec)	Velocity Head (mm WC)	Scrubber Pressure Drop	
					mm WC	Velocity Heads
48	3.81	17.9	18.5	20.2	228	11.3
49		26.2	18.4	20.1	345	17.2
50		35.7	18.4	20.2	516	25.6
51		51.3	18.4	20.2	833	41.3
52		36.4	26.0	40.1	1217	30.3
53		25.4	26.0	40.1	787	19.6
54		18.5	26.0	40.1	516	12.8
55		8.49	26.1	40.4	239	5.92
56		1.38	39.9	94.0	191	2.03
57		5.59	39.6	93.0	442	4.75
58		12.4	39.0	91.4	864	9.44
59		16.9	38.7	91.2	1176	12.9
60		0.52	53.6	173	282	1.63
61		1.03	53.6	173	345	1.99
62		4.12	53.6	173	767	4.42
63		9.00	53.6	173	965	5.59
64		25.3	26.2	41.7	802	19.3
65		12.4	38.4	90.2	870	9.63
66		2.63	52.7	168	517	3.07
67		1.42	39.0	91.7	191	2.08
68		10.7	20.7	25.4	151	5.94
69		8.50	26.4	41.4	223	5.37
70	2.54	38.4	28.2	47.8	1092	22.8
71		53.0	28.7	49.3	1707	34.6
72		36.9	40.5	98.8	2680	27.1
73		26.4	40.5	98.6	1722	17.5
74		15.2	41.5	100	963	9.58
75		14.4	59.7	211	2300	10.9
76		8.26	59.4	210	1247	5.93
77		1.56	80.2	384	1087	2.84
78	3.81	0.505	54.9	177	302	1.71
79		1.41	39.3	92.5	200	2.16
80		8.38	26.4	41.4	217	5.24
81		18.7	18.4	20.1	217	10.8
82		18.5	18.5	20.3	217	10.7
83		18.6	18.5	20.2	217	10.8

Table 5 (Continued)

SCRUBBER PRESSURE DROP DATA FOR AMBIENT SCRUBBING TESTS

Test Code No. EA	Orifice Diameter (cm)	Liquid-to-Gas Ratio (liters/Am^3)	Gas Velocity in Orifice (m/sec)	Velocity Head (mm WC)	Scrubber Pressure Drop	
					mm WC	Velocity Heads
84	2.54	8.22	60.7	214	1290	6.02
85		9.04	59.1	209	1413	6.75
86		10.7	59.1	209	1633	7.81
87		12.6	59.1	209	2000	9.59
88		35.2	40.8	102	2532	24.8
89		25.8	41.1	103	1768	17.2
90		17.7	42.1	105	1224	11.7
91	2.54	17.7	42.4	105	1224	11.6
92		38.3	38.7	88.4	2590	29.3
93		24.0	36.3	78.2	1237	15.8
94		12.4	39.3	89.7	663	7.39
95		3.38	38.7	87.6	292	3.33
96		9.37	26.6	40.9	209	5.12
97		6.93	72.8	307	1854	6.05
98		78.2	27.2	43.9	2946	67.1
99		42.4	37.5	83.8	2642	31.5
100		21.1	50.3	154	2291	14.9
101		9.37	68.0	277	1902	6.87
102		12.8	39.0	89.4	673	7.52
103		38.5	38.7	89.4	2565	28.7
104		9.24	26.9	42.4	224	5.27
105		3.17	39.3	90.4	272	3.00
106		21.7	39.0	89.7	1250	13.9
107	4.45	3.88	20.9	26.4	82.1	3.12
108		2.98	27.3	44.5	136	3.04
109		2.73	29.8	53.3	162	3.04
110	2.54	9.92	18.8	20.5	81.3	3.96
111		8.92	20.9	25.3	97.7	3.85
112		7.06	26.5	40.6	137	3.39
113		6.[illegible]	27.2	42.9	161	3.75
114	3.81	3.74	22.2	29.2	77.8	2.67
115		3.24	25.7	39.1	103	2.64
116		2.82	29.5	51.6	130	2.52
117		2.49	33.5	66.3	164	2.48
118		1.84	30.1	54.1	115	2.11
119		5.52	30.1	54.1	216	3.99
120		8.20	30.0	54.1	293	5.40
121		12.3	30.0	54.1	444	8.20
122		16.0	29.6	53.1	588	11.1
123		4.51	48.5	142	572	4.03

Table 5 (Concluded)

SCRUBBER PRESSURE DROP DATA FOR AMBIENT SCRUBBING TESTS

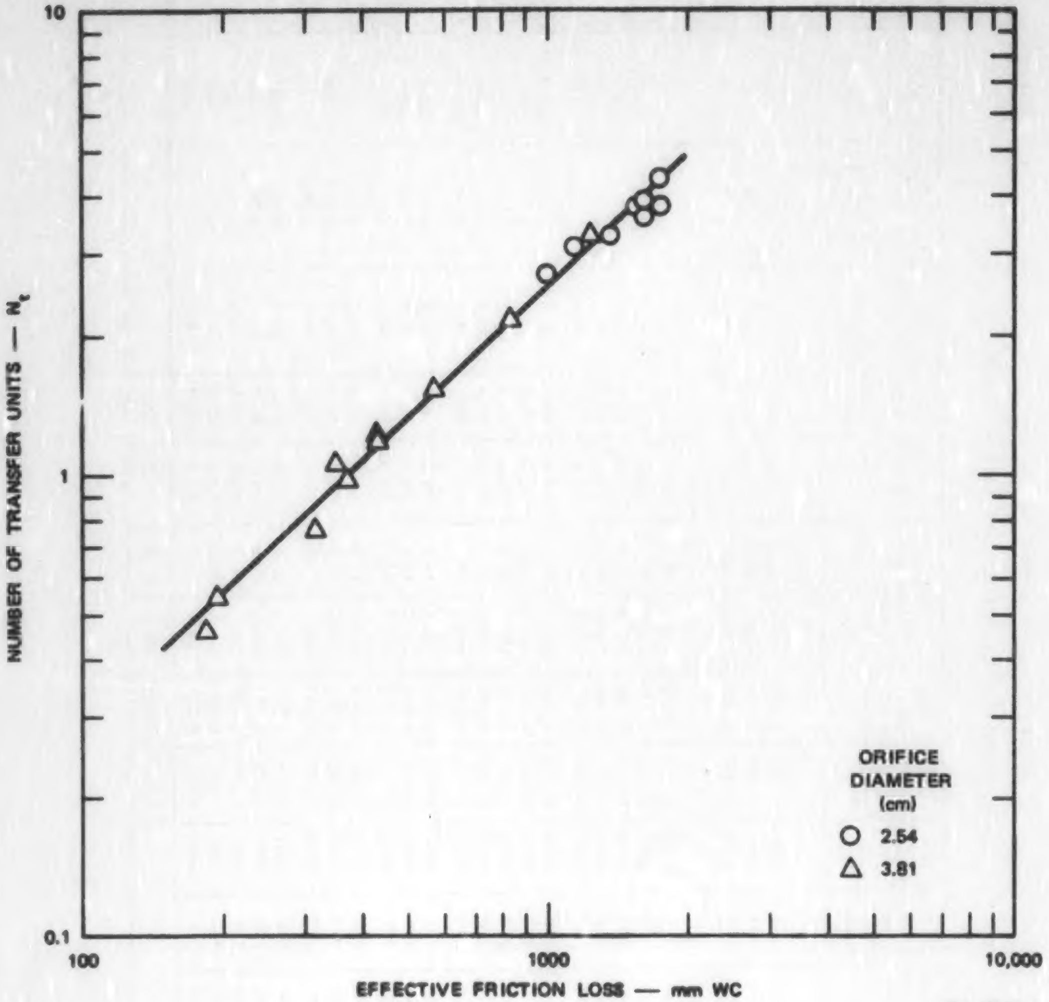
Test Code No. EA	Orifice Diameter (cm)	Liquid-to-Gas Ratio (liters/Am^3)	Gas Velocity in Orifice (m/sec)	Velocity Head (mm WC)	Scrubber Pressure Drop	
					mm WC	Velocity Heads
124	2.54	16.5	38.7	88.6	897	10.1
125		22.0	38.7	88.6	1271	14.3
126		28.1	37.8	87.1	1587	18.2
127		38.0	38.1	87.9	2440	27.8
128		1.77	70.4	297	866	2.92

[a] Calculated at actual inlet gas conditions.

Table 6

SCRUBBER PERFORMANCE DATA FOR ADIABATIC SATURATION SCRUBBING TESTS

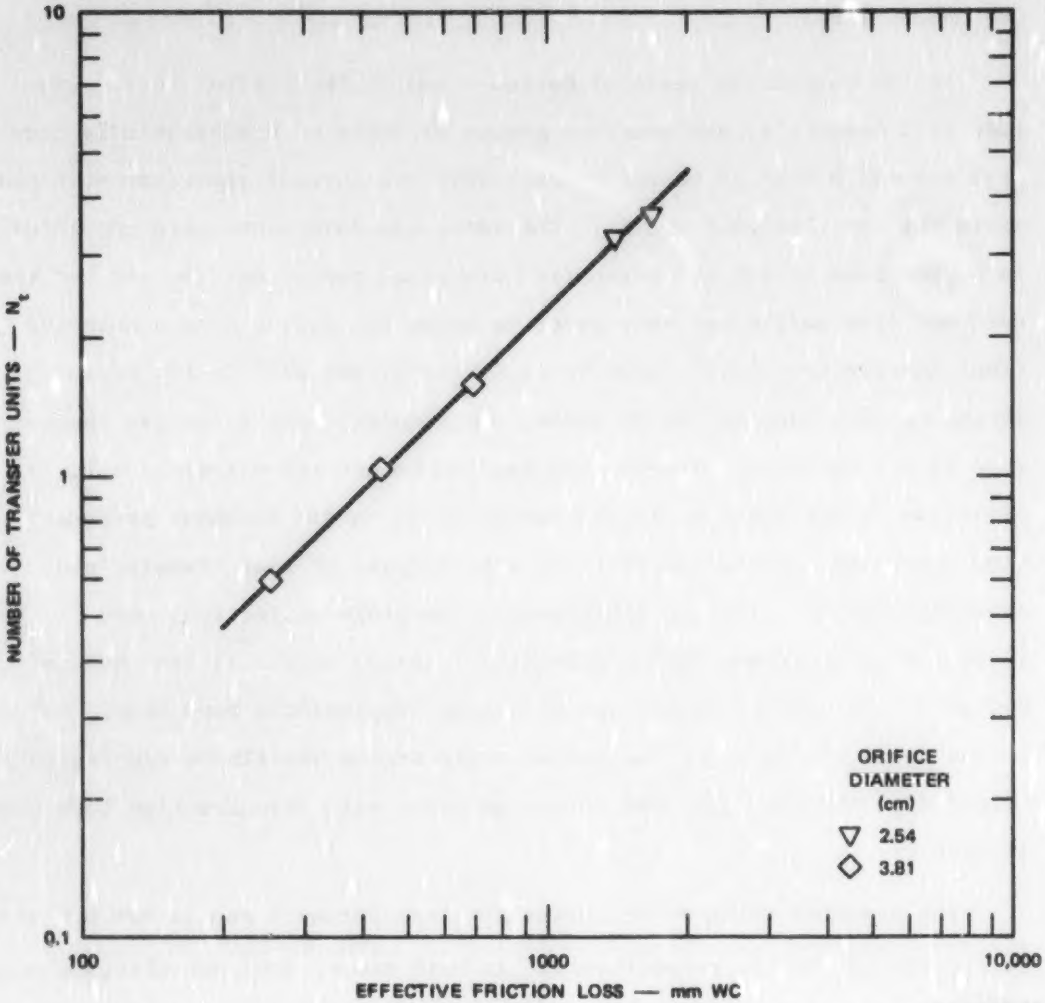
Test Code No.	Aerosol Generation Rate (μg/min)	Contactor Orifice Size (cm)	Inlet Gas Flow Rate (std liters/min)			Gas Moisture Content (g/g dry air)		Gas Temperature ($^{\circ}C$)		Water Temperature ($^{\circ}C$)		Gas Velocity in Orifice (m/sec)	Liquid-to-Gas Ratio $\left(\frac{\text{liters}}{\text{Sm}^3}\right)$	Effective Friction Loss (mm WC)	Collection Efficiency (%)	Transfer Units (N_t)
			Air	Water Vapor	Total	In	Out	In	Out	In	Out					
EN																
2	1060	3.81	1670	923	2590	0.341	0.384	126.1	73.9	74.4	74.4	50.7	4.78	432	69.05	1.17
3	1245		1670	923	2590	0.341	0.384	126.1	73.9	74.4	74.4	50.7	4.78	432	68.61	1.16
4	1370		1670	923	2590	0.341	0.384	126.1	73.9	74.4	74.4	50.7	4.78	432	70.23	1.21
AS																
6	1319	3.81	1580	800	2380	0.315	0.390	128.9	72.2	73.3	73.9	46.9	19.0	1240	95.98	3.21
7	1010		1580	800	2380	0.315	1.369	130	72.2	73.3	73.9	47.0	13.5	837	88.28	2.14
9	1225		1580	800	2380	0.315	0.362	130.6	72.8	73.9	73.9	47.1	8.16	571	77.81	1.51
10	1371		1580	800	2380	0.315	0.350	130.6	72.8	73.3	73.9	47.1	4.69	353	64.86	1.05
11	1176		1580	800	2380	0.315	0.342	127.8	72.8	75.6	73.3	46.8	1.54	197	41.67	0.539
12	2063	2.54	1240	659	1900	0.329	0.485	125	71.1	73.3	73.3	83.5	10.2	1750	98.64	4.30
13	1226		1230	659	1890	0.334	0.467	129.4	70.6	72.8	73.3	83.9	10.3	1750	97.67	3.76
14	1074		1190	573	1760	0.300	0.372	130	70.6	73.3	73.3	78.3	11.0	1620	97.78	3.81
15	1190		1190	573	1760	0.300	0.386	138.9	71.1	73.9	73.9	80.0	11.0	1620	97.14	3.56
16	1007		1190	573	1760	0.300	0.384	123.3	71.7	75.6	74.4	77.0	8.59	1370	96.06	3.23
17	1085	2.54	1150	542	1690	0.292	0.369	128.9	70.6	73.3	73.3	75.0	11.5	1550	97.65	3.75
18	1072		1120	542	1660	0.301	0.355	121.7	71.1	73.3	73.3	72.3	9.02	1150	95.42	3.08
19	997		1120	542	1660	0.301	0.335	125	70.6	73.3	72.8	72.9	5.71	1000	93.21	2.69
20	854	3.81	1580	783	2360	0.308	0.327	128.3	71.7	73.9	73.9	46.5	4.81	371	62.18	0.972
21	885		1580	783	2360	0.308	0.325	128.9	71.7	73.3	73.9	46.5	4.01	319	53.02	0.756
22	942		1580	783	2360	0.308	0.318	130	71.7	73.9	73.3	46.7	1.39	186	36.62	0.456
23	704	2.54	1250	682	1930	0.338	0.389	128.9	71.1	73.9	73.3	85.9	8.36	1660	97.35	3.63
24	665		1240	682	1920	0.343	0.371	128.9	71.1	73.9	72.8	85.3	6.24	1390	96.01	3.22
25	537	3.81	1590	787	2380	0.308	0.344	130	71.7	73.9	73.9	47.2	11.4	688	79.23	1.57
26	661		1560	801	2360	0.319	0.331	130	71.7	73.9	73.9	46.8	6.33	439	64.15	1.03
27	703		1570	787	2360	0.312	0.323	129.4	71.7	74.4	73.9	46.4	3.13	253	44.64	0.591
Averages						0.317	0.369	128.9	71.7	73.9	73.9					



SA-2745-9

FIGURE 13 SCRUBBER PERFORMANCE CURVE FOR ADIABATIC SATURATION SCRUBBING—AEROSOL A

Gas temperatures: Inlet = 128.9°C; Outlet = 71.7°C.



SA-2745-10

FIGURE 14 SCRUBBER PERFORMANCE CURVE FOR ADIABATIC SATURATION SCRUBBING—AEROSOL B

Gas temperatures: Inlet = 128.9°C; Outlet = 71.7°C.

velocity and liquid-to-gas ratio were found to exert no independent influences on collection efficiency (See Appendix B).

CONDENSING TESTS

In the Condensing tests of Series I and II, the initial tests were made with Aerosol A, and separate groups of tests were subsequently made with Aerosol B when it became evident that the aerosol generator mode had again shifted (Tables 7 and 8). The inlet gas conditions were regulated to be the same as for the Adiabatic Saturation tests, but the gas was then scrubbed with sufficient cold water to bring the exit gas to a selected final temperature; 54.4°C (130°F) in Series I, and 37.8°C (100°F) in Series II. For each series of tests, the liquid-to-gas ratio was therefore fairly constant. However, in Series II there was a trend toward reduction of the required liquid-to-gas ratio as the scrubber pressure drop increased, indicating that the efficiencies of heat transfer and dehumidification, like the efficiency of particle collection, were increased by increases in the effective friction loss. In the tests of Series I, the average outlet gas and water temperatures were equal, but in the tests of Series II, the outlet water stream was always substantially colder than the exit gas, and colder at lower effective friction loss than at high.

The scrubber performance curves for Test Series I and II are presented in Figures 15 and 16, respectively. In both cases, good correlations were obtained, and the curves for Aerosol A and Aerosol B were systematically different, as in the Adiabatic Saturation tests. The corresponding curves for Test Series I and II were actually identical; this is obvious from Figure 17, in which the data points for collection of Aerosol A in both Series I and Series II are presented together. The data points for collection of Aerosol B in Series I and II are similarly presented together in Figure 18. It appears that the coincidence of the performance curves

Table 7

SCRUBBER PERFORMANCE DATA FOR CONDENSATION SCRUBBING TESTS, SERIES I

Test Code No.	Aerosol Generation Rate (μg/min)	Contactor Orifice Size (cm)	Inlet Gas Flow Rate (std liters/min)			Gas Moisture Content (g/g dry air)		Gas Temperature (°C)		Water Temperature (°C)		Gas Velocity in Orifice (m/sec)	Liquid-to-Gas Ratio $\left(\frac{\text{liters}}{\text{Sm}^3}\right)$	Effective Friction Loss (mm WC)	Collection Efficiency (%)	Transfer Units (N_t)
			Air	Water Vapor	Total	In	Out	In	Out	In	Out					
EC 4	867	3.81	2140	1230	3370	0.358	0.104	130.6	52.2	12.2	51.1	66.7	3.37	444	74.57	1.37
6	807		2140	1230	3370	0.358	0.104	130.6	52.2	12.2	51.1	66.7	3.37	444	72.94	1.31
7	892		2140	1230	3370	0.358	0.104	130.6	52.2	12.2	51.1	66.7	3.37	444	72.66	1.30
27	808	3.81	1370	691	2060	0.313	0.113	130	54.4	12.8	52.2	40.7	2.94	121	45.76	0.612
28	850		1660	849	2510	0.317	0.115	131.1	54.4	12.8	52.8	49.8	3.09	234	58.79	0.886
29	843		2190	1080	3270	0.306	0.118	131.1	54.4	12.8	54.4	64.8	2.90	398	74.75	1.38
30	801		2680	1380	4070	0.321	0.122	133.3	54.4	12.8	55.0	81.1	2.41	553	83.14	1.78
31	773	2.54	1220	629	1850	0.319	0.119	127.2	53.9	13.3	53.9	81.7	2.78	798	93.85	2.79
32	917		1300	739	2040	0.353	0.122	127.8	53.9	12.8	54.4	90.2	2.97	983	95.46	3.09
33	932		1650	849	2500	0.319	0.131	130.6	53.9	12.8	54.4	111	2.73	1550	97.40	3.65
46	554	3.81	1860	960	2820	0.320	0.119	131.1	55.0	13.9	55.0	55.9	2.75	282	56.04	0.822
47	555		2340	1170	3510	0.310	0.119	131.7	54.4	13.3	55.0	69.7	2.75	467	75.49	1.41
48	607		2920	1450	4370	0.308	0.122	133.3	54.4	13.9	54.4	87.1	2.25	645	84.04	1.83
49	776	2.54	1760	912	1970	0.321	0.139	131.1	54.4	13.9	55.0	87.9	2.62	1710	97.71	3.78
	Averages					0.327	0.117	130.6	54.4	13.3	54.4					

Table 8

SCRUBBER PERFORMANCE DATA FOR CONDENSATION SCRUBBING TESTS, SERIES II

Test Code No.	Aerosol Generation Rate (µg/min)	Contactor Orifice Size (cm)	Inlet Gas Flow Rate (std liters min)			Gas Moisture Content (g/g dry air)		Gas Temperature (°C)		Water Temperature (°C)		Gas Velocity in Orifice (m/sec)	Liquid-to-Gas Ratio $\left(\frac{\text{liters}}{\text{Sm}^3}\right)$	Effective Friction Loss (mm WC)	Collection Efficiency (%)	Transfer Units (N_t)
			Air	Water Vapor	Total	In	Out	In	Out	In	Out					
EC																
8	957	3.81	1740	923	2660	0.330	0.0484	129.4	38.9	12.2	32.8	52.5	7.04	447	79.27	1.58
9	898		1740	923	2660	0.330	0.0484	129.4	38.9	12.2	32.8	52.5	7.04	447	79.65	1.60
10	1216	4.45	1290	690	1980	0.325	0.0440	128.3	37.8	12.2	27.8	28.6	9.78	183	58.83	0.887
11	1122		1660	850	2510	0.317	0.0449	128.3	37.8	11.7	32.2	36.3	7.73	278	66.62	1.10
12	1197		2210	1080	3300	0.305	0.0458	129.4	37.8	11.7	34.4	47.9	6.88	480	80.41	1.63
13	1115		2740	1370	4110	0.312	0.0470	131.7	37.8	11.7	35.6	59.9	5.68	666	87.37	2.07
14	601	2.54	1140	573	1710	0.313	0.0502	127.8	38.3	12.2	36.1	75.6	6.54	938	95.55	3.11
15	690		1140	567	1710	0.310	0.0487	128.3	37.8	11.7	36.1	75.7	6.32	925	94.98	2.99
16	2340		1460	739	2200	0.315	0.0516	128.9	37.8	11.7	36.1	97.6	6.64	1557	99.16	4.78
17	1063		1680	838	2510	0.311	0.0535	128.9	37.2	11.7	35.6	111	6.31	2120	99.24	4.88
18	1256		1250	641	1890	0.319	0.0488	128.3	37.8	11.7	35.6	83.7	6.83	1120	96.46	3.34
19	855		1210	603	1810	0.310	0.0471	126.7	37.2	12.2	34.4	79.8	7.31	1050	95.84	3.18
20	915		1300	660	1960	0.315	0.0494	127.2	37.8	12.2	35.0	86.6	6.95	1210	96.90	3.47
21	981		1400	728	2130	0.321	0.0508	128.3	37.8	12.2	36.1	94.3	6.83	1450	97.87	3.85
22	787		1520	776	2300	0.317	0.0526	128.3	37.8	12.2	35.6	102	6.67	1710	98.48	4.18
23	769		1660	832	2490	0.311	0.0555	129.4	37.8	12.2	35.6	111	6.62	2120	99.00	4.61
23A	854	4.45	1340	634	1970	0.294	0.0453	128.3	38.3	12.2	27.8	28.5	9.52	176	51.02	0.714
24	879		1490	739	2230	0.308	0.0471	128.9	38.9	12.2	--	32.3	8.55	227	58.98	0.891
25	875		1690	849	2540	0.312	0.0447	130	37.8	12.2	30	36.9	8.78	301	68.15	1.14
26	850		1890	960	2850	0.315	0.0451	130.6	37.8	12.8	32.2	41.5	8.26	379	74.22	1.36
43	340	3.81	1910	960	2870	0.313	0.0446	134.4	37.2	12.8	32.2	57.4	8.35	587	80.00	1.61
44	430		2150	1080	3230	0.312	0.0454	133.9	37.2	12.8	33.9	64.5	7.50	726	85.35	1.92
45	510		2350	1180	3530	0.312	0.0479	131.1	37.8	12.8	34.4	70.0	7.13	866	89.17	2.22
50	370	2.54	1530	838	2370	0.339	0.0531	130.6	37.8	13.3	36.1	106	6.54	1790	97.92	3.87
Averages						0.315	0.0404	129.4	37.8	12.2	33.9					

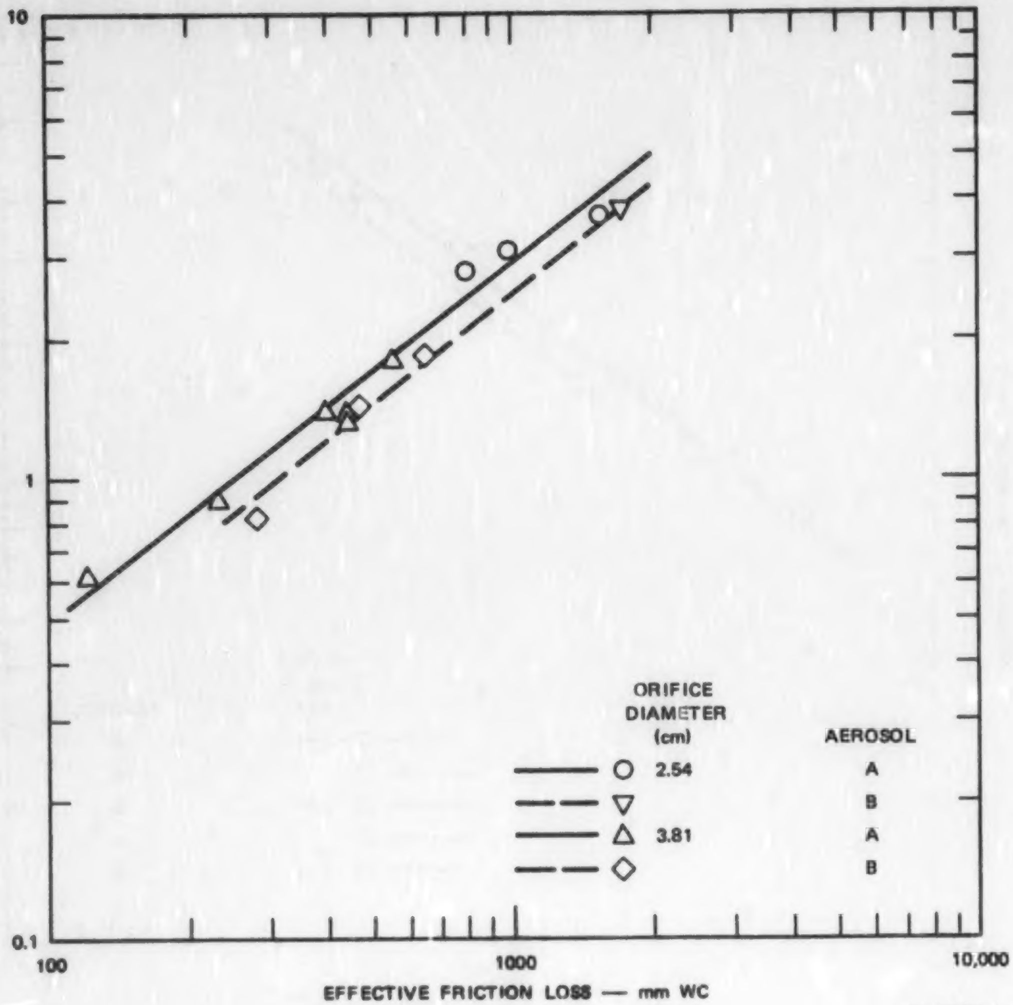


FIGURE 15 SCRUBBER PERFORMANCE CURVES FOR CONDENSATION SCRUBBING (SERIES I)

Gas temperatures: Inlet = 130.6°C; Outlet = 54.4°C.

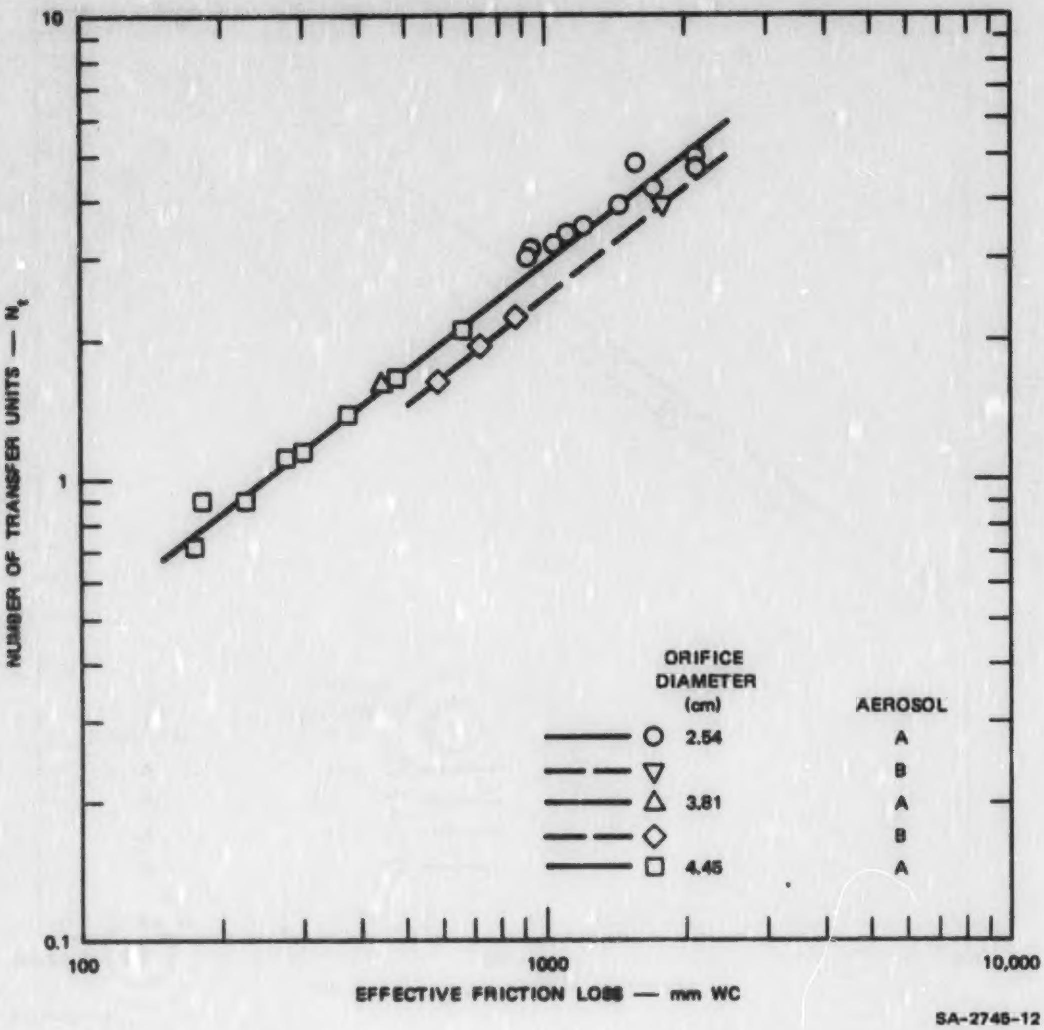


FIGURE 16 SCRUBBER PERFORMANCE CURVES FOR CONDENSATION SCRUBBING (SERIES II)

Gas temperatures: Inlet = 129.4°C; Outlet = 37.8°C.

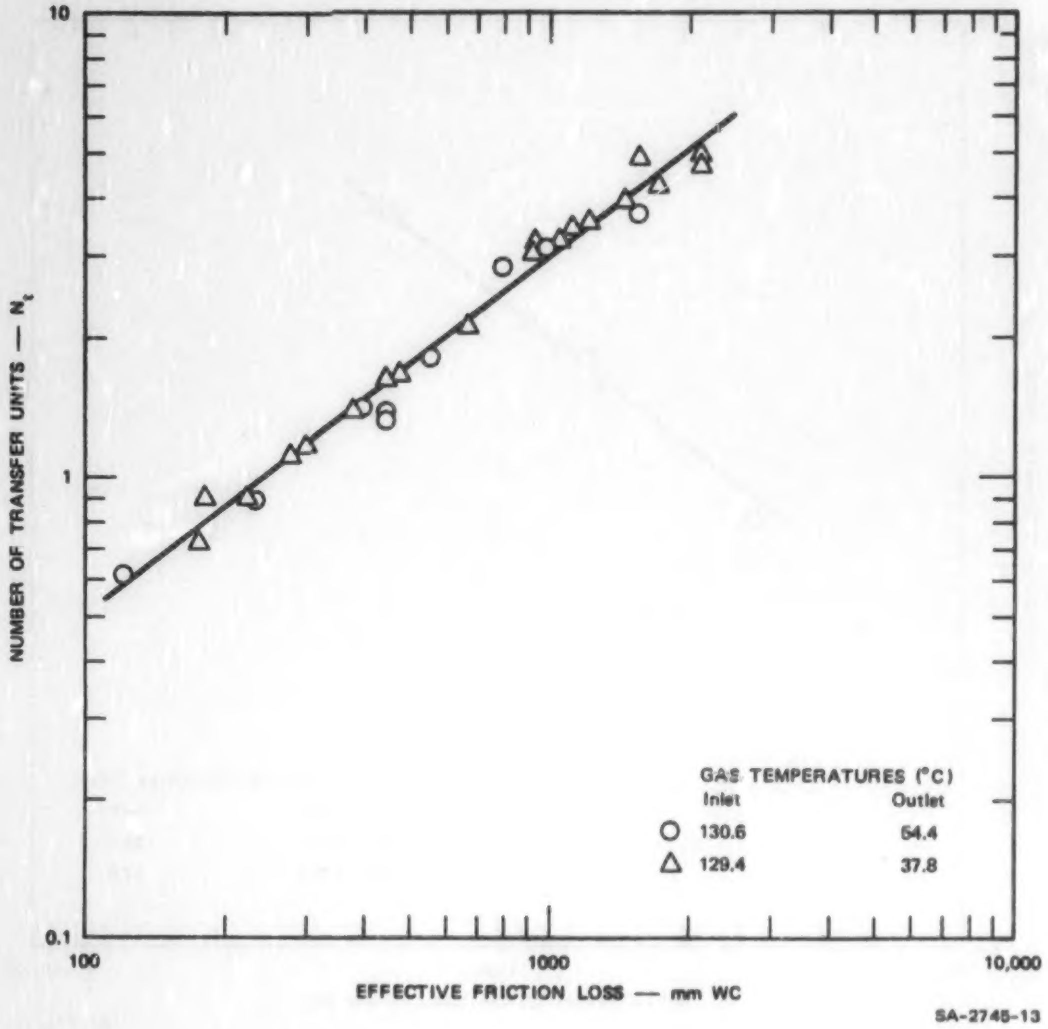


FIGURE 17 SCRUBBER PERFORMANCE CURVE FOR CONDENSATION SCRUBBING (SERIES I AND II)—AEROSOL A

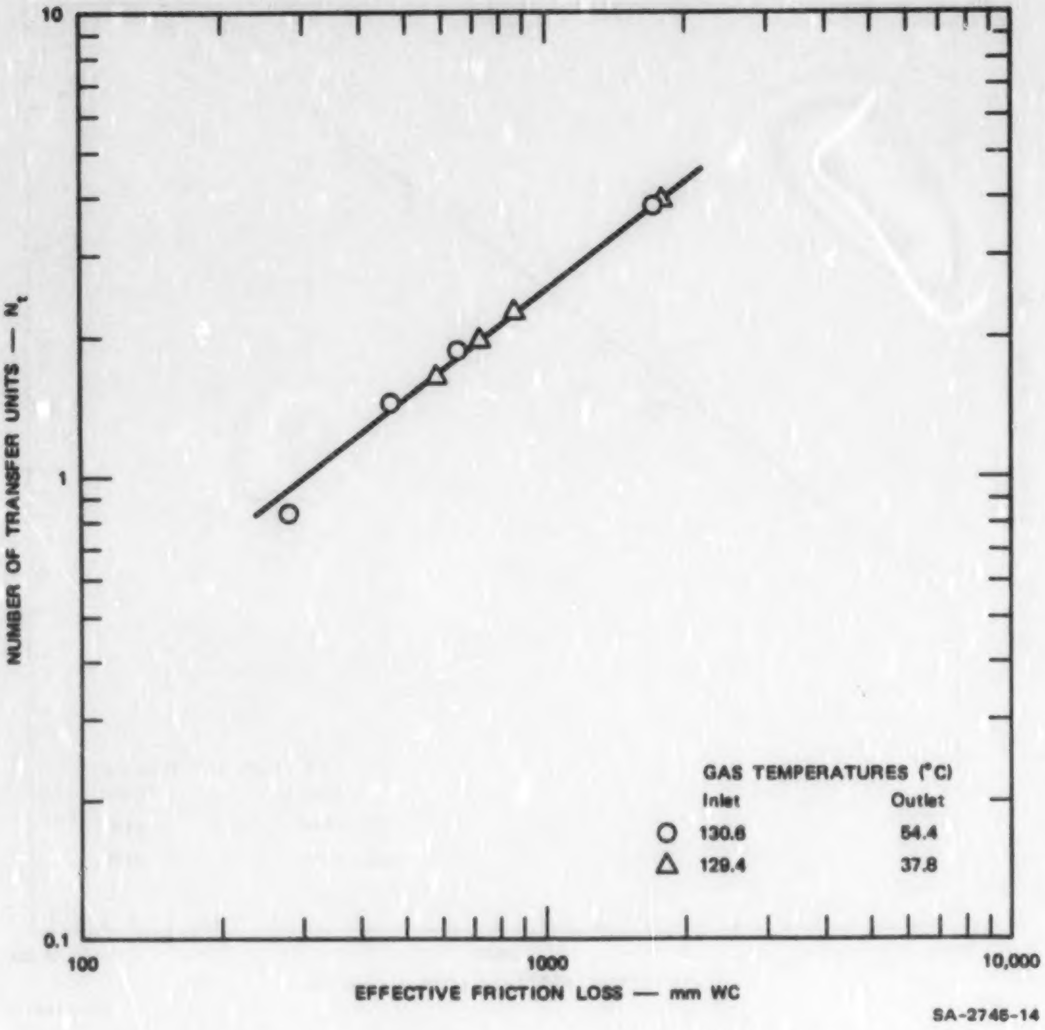


FIGURE 18 SCRUBBER PERFORMANCE CURVE FOR CONDENSATION SCRUBBING (SERIES I AND II)—AEROSOL B

for Series I and II results from the fact that only a relatively small amount of additional water vapor condensed as the gas temperature was reduced from 54.4° to 37.8°C (130° to 100°F).

There was no indication of independent effects of orifice size or gas velocity on the collection efficiency.

In Test Series III the inlet gas was adjusted to the same moisture content as in Series I and II, but the dry bulb temperature was only about 8 Centigrade degrees above the saturation temperature (Table 9). The tests were carried out over the period in which the aerosol generator shifted from producing Aerosol A to producing Aerosol B. Not enough data points were obtained with Aerosol A to establish a performance curve, but it was possible to obtain a curve for Aerosol B (Figure 19), which could then be compared with the similar performance for Test Series I and II (Figure 20). The substantial improvement in performance obtained with the nearly saturated inlet gas probably indicates that condensation started almost immediately in the gas/liquid contacting zone, whereas superheated inlet gas had to be cooled substantially before condensation could start.

VAPORIZING TESTS

The conditions for the Vaporizing tests were chosen arbitrarily to be as similar as possible to those employed in the other test series. The inlet air and water temperatures were adjusted to approximately the same values as in the Adiabatic Saturation tests (Table 10). The water rate was adjusted to yield the same outlet gas temperature in all the runs. The three initial tests (EV-1, -2, and -3) were made as part of the original series of screening tests, on an aerosol that was presumably equivalent to that later designated as Aerosol A. The remainder of the tests were made with Aerosol B, but the data points from Tests

Table 9

SCRUBBER PERFORMANCE DATA FOR CONDENSATION SCRUBBING TESTS, SERIES III

Test Code No.	Aerosol Generation Rate (μg/min)	Contactor Orifice Size (cm)	Inlet Gas Flow Rate (std liters/min)			Gas Moisture Content (g/g dry air)		Gas Temperature (°C)		Water Temperature (°C)		Gas Velocity in Orifice (m/sec)	Liquid-to-Gas Ratio $\left(\frac{\text{liters}}{\text{Sm}^3}\right)$	Effective Friction Loss (mm WC)	Collection Efficiency (%)	Transfer Units (N_t)
			Air	Water Vapor	Total	In	Out	In	Out	In	Out					
EC																
34	918	2.54	1160	629	1790	0.335	0.0477	77.2	37.8	12.8	33.3	69.2	6.86	922	98.04	3.93
35	1015		1230	629	1860	0.318	0.0481	77.2	37.8	12.8	34.4	71.9	6.32	980	97.95	3.89
36	1011		1240	623	1860	0.311	0.0480	80.0	37.8	12.8	34.4	72.5	6.29	978	97.23	3.59
37	936		1660	845	2510	0.319	0.0539	80.0	37.8	12.8	35.6	97.8	6.12	1910	99.28	4.93
38	481		1450	739	2190	0.317	0.0517	80.6	38.3	12.2	37.2	85.5	5.80	1360	97.55	3.71
39	484	3.81	1930	1060	2990	0.340	0.0460	82.8	37.8	12.8	33.9	52.2	7.02	549	87.53	2.08
41	524		1670	838	2510	0.312	0.0450	82.8	37.8	12.8	32.2	43.8	7.23	371	77.61	1.50
42	586		1310	682	1990	0.323	0.0443	80.6	37.8	12.8	27.8	34.5	8.74	242	67.11	1.11
Averages						0.322	0.0481	80.0	37.8	12.8	33.9					

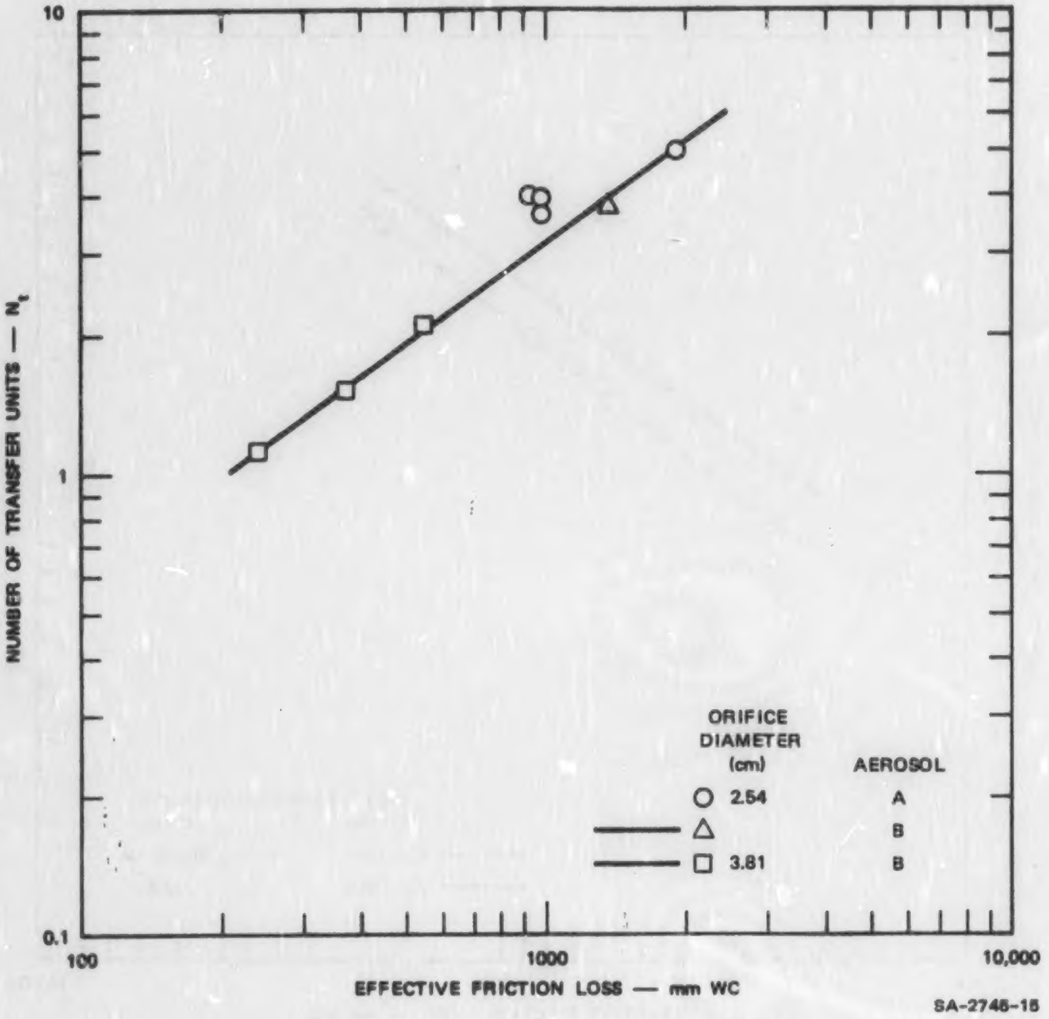


FIGURE 19 SCRUBBER PERFORMANCE CURVE FOR CONDENSATION SCRUBBING (SERIES III)

Gas temperatures: Inlet = 80.0°C; Outlet = 37.8°C.

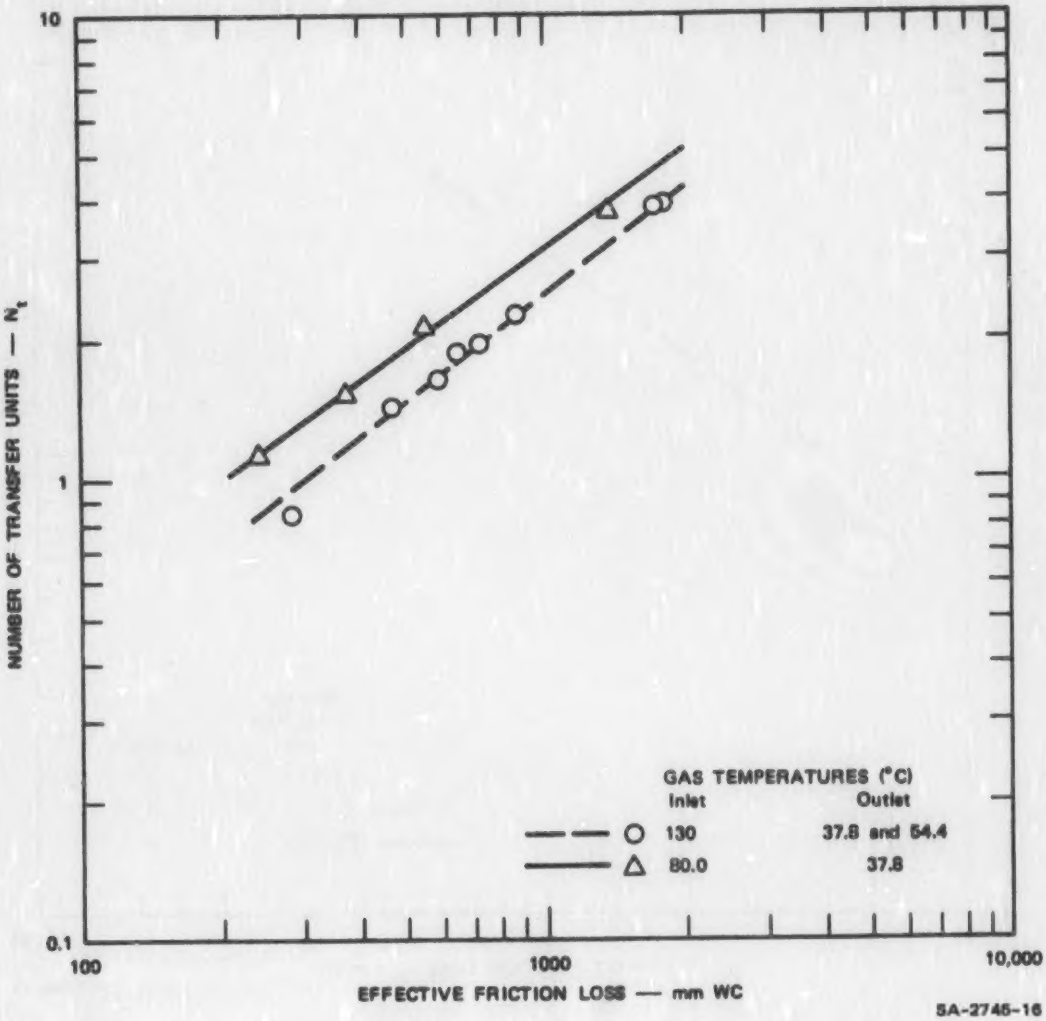


FIGURE 20 SCRUBBER PERFORMANCE CURVES FOR CONDENSATION SCRUBBING OF GASES AT INLET TEMPERATURES OF 80° AND 130°C—AEROSOL B

Table 10

SCRUBBER PERFORMANCE DATA FOR VAPORIZATION SCRUBBING TESTS

Test Code No.	Aerosol Generation Rate (μg/min)	Contactor Orifice Size (cm)	Inlet Gas Flow Rate (std liters/min)			Gas Moisture Content (g/g dry air)		Gas Temperature (°C)		Water Temperature (°C)		Gas Velocity in Orifice (m/sec)	Liquid-to-Gas Ratio $\left(\frac{\text{liters}}{\text{Sm}^3}\right)$	Effective Friction Loss (mm WC)	Collection Efficiency (%)	Transfer Units (N_t)
			Air	Water Vapor	Total	In	Out	In	Out	In	Out					
EV																
1	920	3.81	2250	--	2250	0.01[a]	0.150	126.1	58.9	71.1	58.9	44.0	5.04	430	55.75	0.815
2	990		2280	--	2280		0.147	125.6	58.3	72.8	58.9	44.6	4.99	431	53.69	0.770
3	1050		2280	--	2280		0.147	125.6	58.3	72.8	58.9	44.6	4.99	431	55.56	0.811
4	447	2.54	1720	--	1720	0.006	0.178	128.3	58.9	73.9	60.0	76.4	7[b]	1610	96.04	3.23
5	535		1570	--	1570	0.006	0.159	125	58.3	73.9	60.0	69.0	6.75	1090	90.29	2.33
6	495		1320	--	1320	0.006	0.138	122.8	57.2	73.9	58.3	57.6	4.30	609	76.80	1.46
7	558	3.81	2170	--	2170	0.006	0.147	126.1	58.3	74.4	60.0	42.2	5.01	390	46.30	0.622
8	559		1940	--	1940	0.006	0.145	126.7	58.3	74.4	60.0	38.1	4.77	281	27.43	0.321
9	653		1640	--	1640	0.006	0.132	123.9	57.2	74.4	59.4	32.0	4.38	159	13.82	0.149
Averages						0.007	0.149	125.6	58.3	73.3	58.3					

[a] Estimated.

[b] Estimated from pressure drop.

EV-1, -2, and -3 appeared to fit the correlation curve fairly well (Figure 21).

The scrubber performance curve for Vaporizing conditions is notable for the very marked "break" and the appearance of a quite distinct and separate correlation curve in the low range of effective friction loss, similar to that obtained for Ambient scrubbing of Aerosol B (Figure 6). This phenomenon did not appear in any of the Adiabatic Saturation or Condensation tests.

GENERAL DISCUSSION

The scrubber performance curves for tests at Adiabatic Saturation, Condensing, and Vaporizing conditions are summarized, without data points in Figures 22 and 23. The curves for scrubbing of Aerosol A are presented in Figure 22, and those for scrubbing of Aerosol B in Figure 23. In Table 11, the numbers of transfer units and corresponding collection efficiencies are tabulated for selected values of effective friction loss, for convenient reference.

Although condensation scrubbing is seen to have afforded a significant increase in the collection efficiency at a given level of effective friction loss, the improvement was not extremely marked. The maximum improvement obtained (comparing condensation scrubbing of the nearly saturated gas with the adiabatic saturation scrubbing of the hot gas) was equivalent to reductions of about 25 to 50% in the effective friction loss required to attain a given collection efficiency. This is much less favorable than indicated by previous experience in pilot plant studies of scrubbing fume from Kraft recovery furnaces,[4,5,9] where condensation scrubbing of the hot gas appeared to reduce the required contacting power by about 50 to 70% from that required in adiabatic saturation scrubbing of the same gas. However, the qualitative trends in the results from the

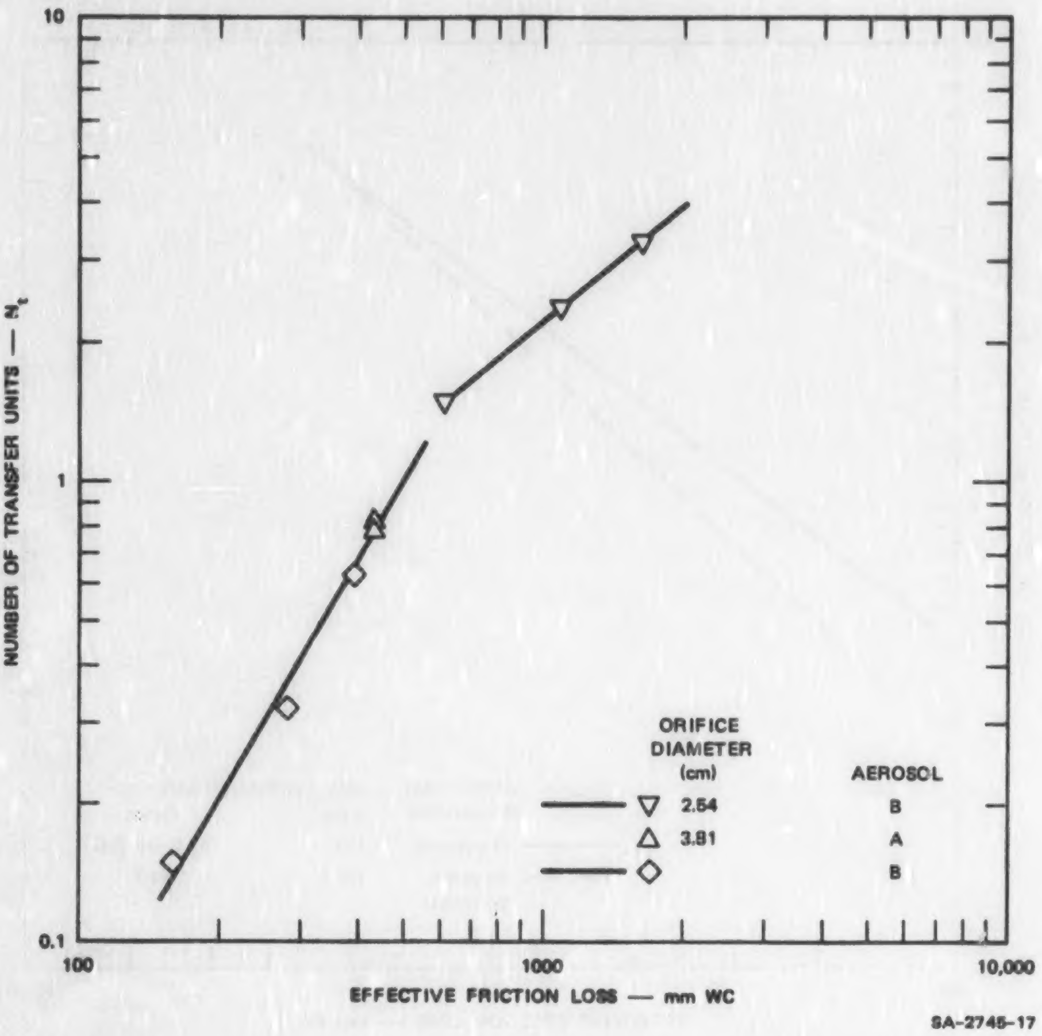


FIGURE 21 SCRUBBER PERFORMANCE CURVE FOR VAPORIZATION SCRUBBING
Gas temperatures: Inlet = 125.6°C; Outlet = 58.3°C.

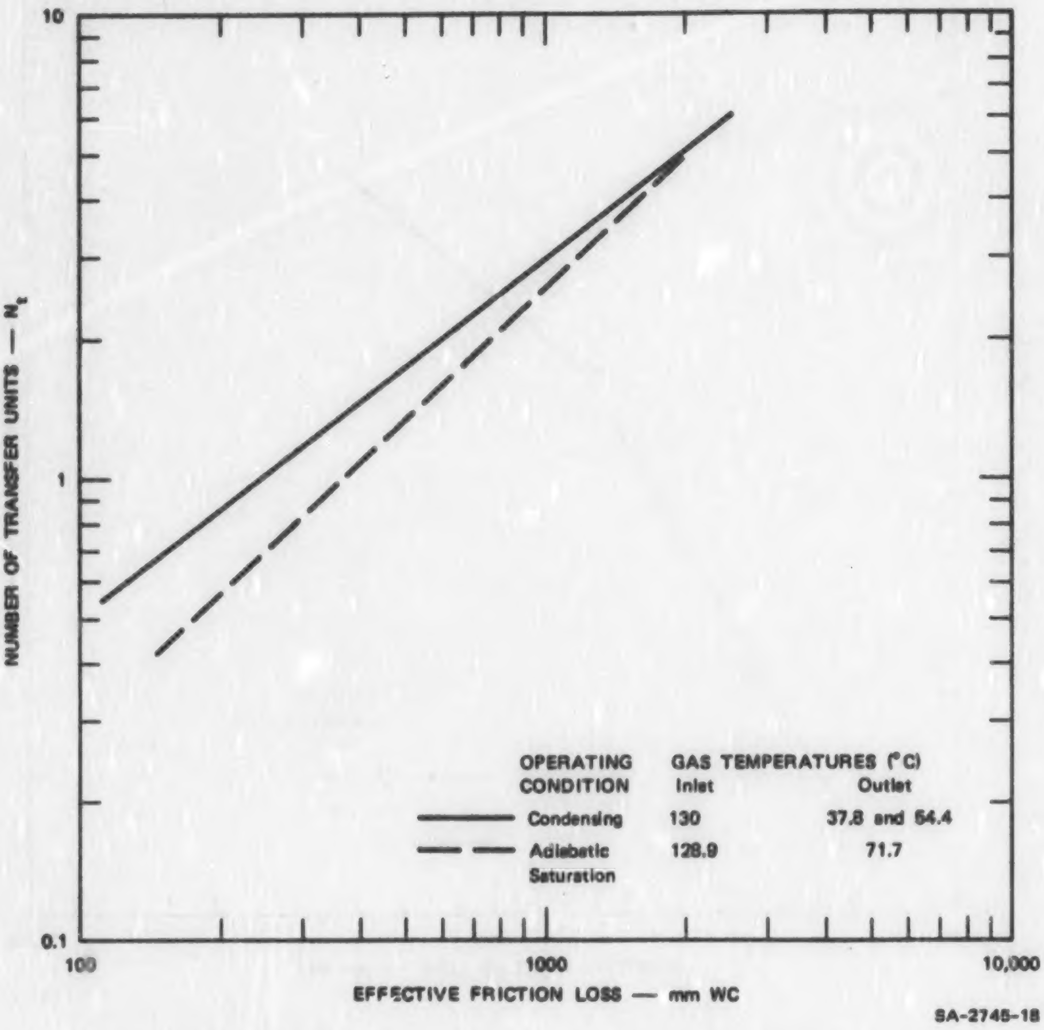
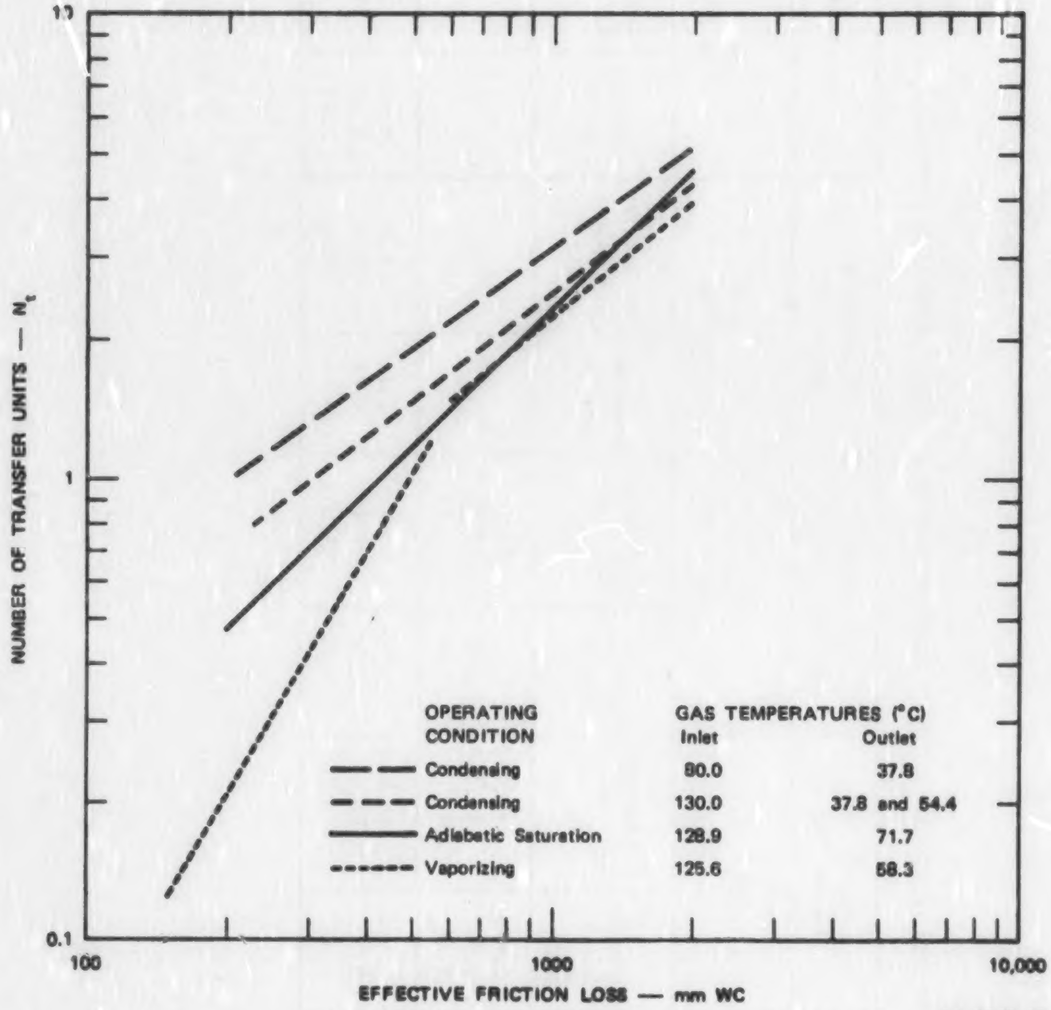


FIGURE 22 SUMMARY OF SCRUBBER PERFORMANCE CURVES FOR ADIABATIC SATURATION AND CONDENSATION SCRUBBING—AEROSOL A



SA-2745-19

FIGURE 23 SUMMARY OF SCRUBBER PERFORMANCE CURVES FOR ADIABATIC SATURATION, CONDENSATION, AND VAPORIZATION SCRUBBING—AEROSOL B

Table 11

SELECTED COMPARISONS OF SCRUBBER PERFORMANCES AT DIFFERENT OPERATING CONDITIONS

Test Condition		Adiabatic Saturation		Condensing Series I and II		Condensing Series III		Vaporizing	
Gas Temp (°C) Inlet Outlet		129 71.7		130 54.4 and 37.8		80.0 37.8		126 58.3	
Aerosol	Effective Friction Loss (mm WC)	Transfer Units	Collection Efficiency (%)	Transfer Units	Collection Efficiency (%)	Transfer Units	Collection Efficiency (%)	Transfer Units	Collection Efficiency (%)
A	250	0.685	49.6	1.01	63.3				
	1000	2.52	91.95	2.93	94.66				
	1500	3.68	97.48	4.00	98.17				
B	250	0.583	44.2	0.840	56.8	1.14	67.8	0.303	26.0
	1000	2.30	90.0	2.46	91.46	3.12	95.55	2.20	88.9
	1500	3.43	96.76	3.36	96.50	4.18	98.47	3.05	95.23

different investigations were similar, and there were wide differences in the natures of the aerosols that might account for the quantitative differences in the performances that were observed.

The scrubber tests clearly demonstrated that liquid-to-gas ratio, gas velocity, and contactor orifice size had no influences on collection efficiency that were independent of effective friction loss, at least over the operating range of major practical interest (see Appendix B). Exceptions to this conclusion may exist in the instances where a separate, steep performance curve appears in the region of low effective friction loss and low collection efficiency. No clear exceptions appeared even in that operating region, but since the pertinent data obtained were relatively imprecise and few in number, and covered relatively narrow ranges of variables, some exceptions may have been concealed. However, the operating region is not often one of much practical importance.

This observation concerning liquid-to-gas ratio is consistent with the experience obtained in other investigations with both similar and some dissimilar types of scrubbers, although it conflicts with reports from some other investigators (see Appendix A). Where condensation and vaporization phenomena are controlled by liquid-to-gas ratio, this factor can be expected to have independent effects on efficiency. However, in Condensation tests, Series I and II, where additional gas cooling did not effect substantial additional condensation of water, liquid-to-gas ratio again appeared to have no independent effects.

The results of the investigation have thus constituted an additional verification of the "contacting power rule" as applied to a small replica of the generalized class of commercial "venturi" scrubbers. (Most current venturi scrubbers are actually orifice scrubbers employing some form of variable-area orifice.) Deviations between the various performance curves are therefore ascribable to introduction of additional mechanisms--

in the present case, vaporization and condensation.

Where diffusion and heat transfer effects come into play, as in condensation scrubbing, it is not to be expected that performance should be dependent only on contacting power and be independent of scrubber configuration. To the extent that particle scrubbing is an inertial phenomenon, efficiency should be--and apparently is--independent of contact time. However, where diffusion and heat transfer are involved, contact time and scrubber configuration should play roles. Power consumption does, of course, affect mass transfer as well as particle collection. A number of investigators have now produced empirical correlations of gas absorption data for cocurrent contactors (particularly pipeline contactors) in terms of energy dissipation (see Appendix A). There should thus be relationships between contacting power and particle collection by Stefan flow and probably also between contacting power and the growth of particles by condensation of water vapor, but these relationships are presumably quite different from that between contacting power and particle collection by inertial deposition. The scrubber performance curve for condensation scrubbing thus represents the net effects of at least two major particle collection mechanisms, each being a different function of contacting power.

Qualitatively, at least, it does not appear that condensation scrubbing should be regarded as a possible way to eliminate use of energy in contacting, since utilization of condensation phenomena will also demand contacting power. Rather, it should probably be regarded as a way merely of reducing contacting power requirements. Of course, condensation scrubbing will, in practice, incur some energy consumption elsewhere (in water cooling, for example) that will partly counteract the saving.

Where diffusional phenomena, such as Stefan flow, are involved, it may be advantageous to use a type of gas/liquid contactor that provides a relatively long contact time rather than one (such as a venturi or orifice) that gives an intense but short contact. A pipeline contactor operating in the spray-flow regime appears to be a promising device meeting this objective.

Since the results of this investigation clearly indicate a major improvement from presaturating the gas before condensation scrubbing, a high-energy condensation scrubber should be preceded by a low-energy gas/liquid contactor designed to operate as an adiabatic saturator by recirculation of the water. The presaturator would not be designed to collect fine particles.

It was also indicated that in condensation scrubbing there is minimal, if any, benefit from reducing the final gas temperature below about 50°C, since the additional condensation of water vapor is small. Hence, it should not be necessary to use very cold scrubbing water unless there are other reasons to dehumidify the gas. On the other hand, there may an advantage in increasing the saturation temperature of the inlet gas, since the quantity of water vapor present in the gas increases rapidly with temperature. This approach incurs the extra costs not only of humidifying the inlet gas but of removing the increased load of low-level heat from the scrubbing water. Such economic considerations are further discussed in Appendix C.

A number of phenomena appearing in this investigation may be of major significance, theoretical or practical, but at this point they lack explanation or--in some instances--complete confirmation of their reality.

The straight-line relationship in log-log plots of scrubber performance was generally well confirmed by the results of this investigation. However, the relationship is empirical, and at present there is no basis other than experience for assuming that the performance curves should be straight lines in the general case. Calvert's model for the venturi scrubber (see Appendix A) leads to an approximation that, for a monodisperse aerosol of given diameter, the number of transfer units is directly proportional to the pressure drop; hence, the predicted curve of transfer units versus pressure drop on a log-log plot is a straight line with a slope of unity. For a polydisperse aerosol, the overall collection efficiency would have to be determined by integrating the collection efficiencies over the range of particle sizes represented in the particle-size distribution. Presumably, then, the form of the scrubber performance curve should be dependent on the nature of the particle-size distribution, and it is not obvious that the curve should necessarily be straight.

For the present, there is no theoretical basis for the applicability of the "contacting power rule" to various types of scrubbers that do not fit the models of Calvert and other investigators. If it can be assumed on the basis of experience to date that scrubber performance curves are straight lines on log-log plots, then it also appears logical that for a monodisperse aerosol, the slope of the curve should be unity, with successive equal increments of contacting power producing equal increments in the number of transfer units. There is no experimental confirmation of this conjecture, since no appropriate data are available for the scrubbing of a truly monodisperse aerosol. In scrubbing of a polydisperse aerosol, larger particles will be collected with higher efficiency than smaller ones, and successive increments of contacting power should yield successively smaller increments of transfer units, leading to a performance curve with a slope of less than unity. In fact, it has been found that the performance curves for most aerosols are straight lines with slopes less than unity. However, some data developed from the literature have yielded curves having slopes greater than unity.[4] If the collection mechanism is assumed to remain the same, such a performance curve implies that the aerosol increases in average particle size in passing through the scrubbing process. This interpretation, in turn, implies either that the finer particles are collected selectively, which is contrary to experience and reasonable expectation, or that the aerosol undergoes a coagulation process in the scrubber that is also related to contacting power, which would seem possible but unlikely.

The present investigation is apparently the first to indicate that the observed straight-line relationship in scrubber performance curves may sometimes break down in some part of the contacting power range--specifically, the low range. No indication of comparable deviations in the high contacting power range has yet appeared. If it is accepted that the performance curve is a straight line, then it appears reasonable that it should remain so over the entire contacting power range, unless different particle collection mechanisms predominate in different parts of the range.

In the present investigation, there were four occasions in which separate correlation curves appeared in the low contacting power region (Figures 6, 7, 8, 21). In two of these cases, the curves were reasonably well defined (Figures 6, 21), and appear to be straight, or nearly straight lines. Also, the slopes of these curves exceeded unity. However, in each case, the principal correlation curve in the upper contacting power range was a straight line with a slope less than unity. This behavior suggests that in the cases reported in the literature where correlation curves with very steep slopes were encountered, data may have been taken only over a range defining the lower curve; extending the data to a higher contacting power range might have revealed a second curve of more familiar character.

It also appears that the steep curves in the low-energy region were most pronounced in those cases in which the aerosol was presumably the finest, at least in average particle size.

These observations suggest that the appearance of two segments in the scrubber performance curve for an aerosol may indicate a change in the dominant particle-collection mechanism over the contacting power range in which the steeper correlation curve appears--for instance, a shift from Brownian diffusion to inertial deposition. At present, this hypothesis is--at best--highly speculative, but it does suggest experimental methods of attack on the problem.

A less rarified explanation for the low-energy-range performance would be channeling of liquid in the contactor. Such channeling might indeed explain behavior with very low water and air rates, but it does not seem adequate to explain behavior such as shown in Figures 6 and 21, or the absence of comparable behavior in other test series.

In cases where scrubbing tests on evidently different aerosols are involved (Figure 11), crossing of the performance curves appears readily explainable in terms of differences in particle-size distributions as well as average particle sizes. However, in cases where the same aerosol is being scrubbed at different operating conditions (Figure 23), it is difficult to offer a satisfying physical interpretation for a crossing of performance curves. Differences in collection mechanisms, as in the cases of Adiabatic Saturation and Condensation scrubbing, can offer a reason--if not a detailed explanation--why the performance curves have different slopes. Since the curves do have different slopes, they must at some point either intersect or merge. If they merge, the straight-line relationship for at least one of the curves must break down. So far, there has been no evidence of such breakdowns in performance curves at high contacting powers and high efficiencies.

The apparent intersection of the performance curves for Adiabatic Saturation scrubbing and Condensation scrubbing in Figure 23 occurs near the upper end of the range in which data were obtained, so that a merger of the curves, rather than an intersection, may have been concealed by lack of experimental precision. Nevertheless, there is no unequivocal evidence that this was, in fact, what happened.

To illuminate some of these questions, the performance of the scrubber should be investigated with aerosols of different particle sizes, generated by atomizing ammonium fluorescein solutions of different concentrations. Aerosols should be used that are both larger and smaller than the one used in the present investigation. Any trends appearing in the observed phenomena as a result of known changes in particle size should provide much better bases for interpretation.

REFERENCES

1. Christoforidis, A. J., J. F. Tomashefski, and R. I. Mitchell, Use of an Ultrasonic Nebulizer for the Application of Oropharyngeal, Laryngeal, and Tracheobronchial Anesthesia. CHEST 59 (6), 629-633 (June 1971).

2. Ferber, B. I., F. J. Brenenborg, and A. Rhode, Penetration of Sodium Chloride Aerosol Through Respirator Filters. Amer. Ind. Hyg. Assoc. J. 33 (12), 791-796 (December 1972).

3. Lapple, C. E., and H. J. Kamack, Performance of Wet Dust Scrubbers. Chem. Eng. Prog. 51 (3), 110-121 (March 1955).

4. Semrau, K. T., Dust Scrubber Design--a Critique on the State of the Art. J. Air Poll. Control Assoc. 13 (12), 587-594 (December 1963).

5. Semrau, K. T., C. W. Marynowski, K. E. Lunde, and C. E. Lapple, Influence of Power Input on Efficiency of Dust Scrubbers. Ind. Eng. Chem. 50 (11), 1615-1620 (November 1958).

6. Stevens, H. R., and H. B. Albregt, Assessment of Ultrasonic Nebulization. Anesthesiology 27 (5), 648-653 (September-October 1966).

7. Stöber, W. and H. Flachsbart, An Evaluation of Nebulized Ammonium Florescein as a Laboratory Aerosol. Atmos. Environ. 7 (7), 737-748 (July 1973).

8. Stöber, W., H. Flachsbart, and C. Boose, Distribution Analyses of the Aerodynamic Size and the Mass of Aerosol Particles by Means of the Spiral Centrifuge in Comparison to Other Aerosol Precipitators. J. Coll. Interface Sci. 39 (1), 109-120 (April 1972).

9. West, P. H., H. P. Markant, and J. H. Coulter, New Venturi Scrubber Developments. The Steam-Atomized Venturi. Tappi 44 (10), 710-715 (October 1961).

GLOSSARY

Actual Conditions (gas) - The actual temperature and pressure of a gas at the point of reference.

Collection Efficiency - The fraction (η) or percentage (100η) of an aerosol entering a collection device that is removed from the gas stream by the device.

Contacting Power - The power that is dissipated in fluid turbulence (and ultimately as heat) in the gas and liquid phases during gas/liquid contacting in a scrubber. It is commonly expressed in units of power per unit of volumetric gas flow rate:

Kw(1000 m^3/hr) or Kwh/1000 m^3	Metric units
hp/1000 (ft^3/min)	English units

Diffusiophoresis - Movement of particles through a nonuniform gas resulting from the existence of concentration gradients. It is produced by the uneven molecular bombardment of the particles due to gradient in gas composition.

Effective Friction Loss - The equivalent of contacting power, expressed in terms of equivalent gas pressure drop (due to friction loss only) across the gas/liquid contactor. In most cases, it is approximately equal to the actual gas pressure drop across a device that takes all its contacting power from the gas stream. It is commonly expressed in the same units as gas pressure drop:

mm WC (millimeters of water column)	Metric units
inches WC (inches of water column)	English units

Liquid-to-Gas Ratio - The ratio of the volumes of liquid and gas brought into contact in a gas/liquid contactor. It may be expressed on the basis of the gas volume either at actual or at standard conditions:

liters/Am^3 (liters of water per actual cubic meter of gas)	Metric units
liters/Sm^3 (liters of water per standard cubic meter of gas)	
gal/1000 Aft^3 (gallons of water per 1000 actual cubic feet of gas)	English units
gal/1000 Sft^3 (gallons of water per 1000 standard cubic feet of gas)	

Scrubber Performance Curve - A correlation curve expressing the functional relationship between the number of transfer units and the contacting power (or effective friction loss). This is most conveniently presented on a log-log plot.

Scrubber Pressure Drop - The total drop in gas pressure across a gas scrubber, whether due to friction loss or to kinetic energy changes. It is commonly expressed as the equivalent fluid head loss:

mm WC (millimeters of water column)	Metric units
inches WC (inches of water column)	English units

It may also be expressed in dimensionless form as the number of velocity heads, based on the gas velocity at the entrance to the gas/liquid contactor or some other suitable entry point to the scrubber.

Standard Conditions (gas) - The selected reference temperature and pressure for specification of gas volumes. In this report, the standard conditions are 25°C (77°F) and 1 atm pressure.

Stefan Flow (also, Stephan Flow) - The net convective gas flow produced by the diffusion of vapor away from a surface where evaporation of liquid is taking place, or by diffusion of vapor toward a surface where condensation is taking place. (Definition specific to circumstances of interest to aerosol deposition.)

Transfer Unit - Defined by the relationship

$$N_t = \ln\left(\frac{1}{1-\eta}\right)$$

where N_t = number of transfer units and η = fractional collection efficiency.

Velocity Head - The kinetic energy per unit mass of a flowing fluid, expressed in terms of fluid head:

mm WC (millimeters of water column)	Metric Units
inches WC (inches of water column)	English Units

CONVERSION FACTORS

Gas Flow

$1\ m^3/hr = 0.58857\ ft^3/min$

$1\ liter/min = 0.035316\ ft^3/min$

Gas Velocity

1 m/sec = 3.2808 ft/sec

Liquid Flow

1 liter/min = 0.26418 gal/min

1 liter/hr = 0.0044030 gal/min

$1\ m^3/hr = 4.4029\ gal/min$

Liquid-to-Gas Ratio

$1\ liter/m^3 = 7.4808\ gal/1000\ ft^3$

Contacting Power

$1\ Kw/1000\ (m^3/hr) = 2.2784\ hp/1000\ (ft^3/min)$

Effective Friction Loss

1 mm WC = 0.039370 inch WC

$1\ mm\ WC = 2.724 \times 10^{-3}\ Kw/1000\ (m^3/hr)$

$1\ inch\ WC = 0.1575\ hp/1000\ (ft^3/min)$

Aerosol Concentration

$1\ g/m^3 = 0.43699\ grain/ft^3$

$1\ \mu g/m^3 = 4.3699 \times 10^{-7}\ grain/ft^3$

$1\ g/liter = 436.97\ grains/ft^3$

$1\ \mu g/liter = 4.3697 \times 10^{-4}\ grain/ft^3$

APPENDIX A

LITERATURE REVIEW*

Although particulate scrubbers went into use long ago, sometimes with marked success, their wider application was long hampered by the lack of any systematic procedure for designing--or even for selecting--units for a specific application and specific duty. In a general way, a number of investigators had noted that high scrubber collection efficiency generally coincided with high power consumption, but this was regarded mainly as a disadvantage to be circumvented in some way if possible. The recognition by Lapple and Kamack[14] that the relationship of scrubber collection efficiency to power consumption was actually a functional one did not eliminate the disadvantage of high power consumption, but did provide a highly useful if empirical method for designing scrubbers for a given service. Later development[19,20,21] of this method for correlating scrubber performance data led to the "contacting power concept" which has become, over the past 20 years, a widely accepted basis for practical scrubber design, employed by many manufacturers as well as users of scrubbers.

The current demand for higher collection efficiencies for fine particles has led to increased interest in possible additional particle collection mechanisms that might accentuate the efficiencies of scrubbers without further raising the power requirements. The use of water vapor condensation phenomena was also suggested many years ago, but there has been very little information presented to show what might be the magnitude of such effects in practical scrubbing systems. At least two quite different mechanisms are involved.[5,19] One is the buildup of particles that act as nuclei for the condensation of water vapor into droplets; this action increases the effective size of the particles, making their deposition by the inertial mechanism easier. This mechanism has, until recently, received the most attention from research workers and others. The other mechanisms, diffusiophoresis and Stefan flow, are directly diffusional in nature, and have received appreciable attention only in the last 25 years.

---

*The references cited in this appendix are collected at the end.

The available literature on scrubbers to 1962 was reviewed from the standpoint of the contacting power correlation by Semrau et al,[19,20,21] following the pioneering paper by Lapple and Kamack.[14] Walker[27] and Walker and Hall[28] also used the contacting power basis in correlating their own experimental data on scrubber efficiency as well as some data from the literature.

Since 1963, most of the papers on scrubbers (other than those that were purely descriptive) have fallen into two classes. The first consists of those papers that treat applications and present some efficiency data, or correlations of efficiency data, on the empirical basis of gas pressure drop or some other expression of contacting power. Such papers have contributed additional confirmation of the validity of the contacting power concept but have not presented extensions of the earlier work. A few empirical or semiempirical studies have attempted more systematic approaches, and have reported either general agreement with the contacting power concept, or some exceptions to it.

The second class of papers in this period has consisted mostly of theoretical approaches to the problem of scrubber operation and design, not usually accompanied by much, if any, experimental data for confirmation of the theory. Most of these theoretical studies have treated the case of the venturi scrubber.

Studies of condensation effects to date have been largely theoretical or speculative in nature, but a number of laboratory investigations have been carried out in recent years. Most of the latter have dealt with basic phenomena and did not attempt to treat applications to practical scrubbing equipment. There has been almost no quantitative information reported on the magnitude of the effects attainable in actual scrubbing equipment.

POWER CONSUMPTION AND SCRUBBER EFFICIENCY

In experimental studies, Walker[27] observed that the flooded-disc (annular orifice) scrubber gave efficiencies on black liquor recovery furnace fume that agreed well with those previously obtained[19,20,29] with venturi scrubbers. He also demonstrated improvements in the efficiences obtained by electrostatic pre-agglomeration of the fume. In subsequent studies of the flooded-disc scrubber, Walker and Hall[28] concluded that collection efficiency was dependent on the gas pressure drop and was independent of gas velocity and liquid-to-gas ratio. They also concluded that there was little effect of scrubber size on the efficiency/pressure drop relationship.

Taheri and Haines[23] studied the performance of a pilot-plant venturi scrubber on a test aerosol generated by drying a spray of a solution of methylene blue. They investigated the effects of three methods of water injection: (1) injection through spray nozzles at the throat, (2) injection through continuous slots at the throat, and (3) injection through a weir at the beginning of the venturi convergence. They reported that injection of the water through the weir produced a given efficiency for about 10% less pressure drop than did the other two methods of water injection. They did not report any effects of gas velocity or liquid-to-gas ratio. Their data on outlet aerosol concentrations show considerable scatter that may have resulted from variations in the aerosol particle size.

Taheri et al.[24] studied the efficiency of a pilot plant scrubber using a butterfly valve as an adjustable orifice contactor. They used a methylene blue aerosol, measuring the efficiencies in different particle-size ranges by sampling at the inlet and outlet of the scrubber with cascade impactors. For particles in two size ranges, 1.0-3.0 microns and under 0.6 micron, efficiencies were shown as functions of pressure drop, with no significant independent effects of liquid-to-gas ratio or butterfly valve opening. For the intermediate-sized particles, 0.6-1.5 microns, there were apparent, marked independent effects of liquid-to-gas ratio and angle of opening of the valve. The authors do not appear to suggest a clear explanation for this behavior, although they report an interaction of inertial and diffusional collection mechanisms in the intermediate particle-size range.

In another study with the same experimental system, but using fixed orifice contactors, Taheri et al.[25] reported that a 1.5-inch contactor orifice gave higher efficiencies at given pressure drops than did a 1.0-inch orifice, except in the high pressure drop range. They also reported that there were independent effects of liquid-to-gas ratio, as well as of orifice size, in the lower pressure drop range. However, all the tests in the lower pressure drop range were apparently made with low or very low liquid-to-gas ratios, which might well show independent effects and lead to independent effects of orifice size as well.

A number of investigators have made theoretical analyses of the venturi scrubber, but few of them have attempted experimental verification of the theoretical models. Boll[2] developed a model for the venturi scrubber, and attempted to fit the data of Güntheroth,[9] but acknowledged that the agreement was only fair. Among major experimental investigators, Güntheroth appears to make the strongest claims that venturi geometry, gas velocity, and liquid-to-gas ratio have major independent effects on efficiency.[10]

Behie and Beeckmans[1] developed a mathematical model of venturi scrubber performance and attempted an experimental verification, but without attempting to correlate efficiency as a function of gas pressure drop. Plots of their data suggest that the actual particle sizes of their test aerosols may have varied considerably during some tests.

Calvert et al.[3,5] developed a mathematical model for the operation of venturi and other atomizing scrubbers. They later extended this analysis to present the efficiency of the scrubber as a function of the gas pressure drop.[4] Their design equations for particle penetration through the scrubber[4] depend on experimental evaluation of one of the parameters, which may then absorb the effects of various actual deviations from the theoretical development. It does not appear that the Calvert model has yet received extensive experimental verification or evaluation.

CONDENSATION SCRUBBING

The possibilities of using condensation phenomena to assist in scrubbing of particulates have long been considered and were discussed at length by Harmon[11] in 1938 with specific reference to the cleaning of blast furnace gas. The earlier suggestions were made almost entirely with reference to the buildup of aerosol particle size by using the aerosols as nuclei for the condensation of water vapor. However, more recent theoretical and experimental studies[7,8,15,16,22] have treated the phenomena of diffusiophoresis and Stefan flow. Many studies have been entirely theoretical, but in recent years there have been a number of laboratory investigations[7,8,15,16] that have clearly demonstrated the existence and nature of the phenomena. However, there has been very little information to indicate the magnitude of possible effects in practical or conventional scrubbing equipment. Apparently, the first published data of this sort were those of Semrau et al,[21] who found different relationships between contacting power and collection efficiency in the scrubbing of Kraft recovery furnace fume with hot and cold water. West et al.[29] later obtained very similar data, although they did not ascribe the differences in scrubber performance to condensation phenomena. Other reports of the improvement of industrial scrubber performance by scrubbing with cold water have been qualitative.

Calvert et al.[6] have recently presented a theoretical analysis of the use of condensation scrubbing for collection of fine particles. They also obtained some data on the efficiency of collection of a submicron aerosol by a single sieve-plate. The sieve-plate collector had a low pressure drop and only small amounts of water vapor were condensed during the tests. The measured collection efficiencies, which ranged from 11 to 31%, were compared with the values predicted by the theory developed by the investigators. Apparently, no data were obtained on the efficiency of the device in the absence of water vapor condensation.

It is noteworthy that in recent years a number of investigators[12,13,17] have successfully correlated mass-transfer data in cocurrent contactors as functions of energy dissipation. Most such correlations have been developed for various forms of pipeline contactors but at least one of the studies was made of a packed column with cocurrent gas and liquid flows.[17] The similarities of these correlations to the contacting power correlation for particle collection is obvious. The existence of these correlations strongly suggests that in practical scrubbing equipment, particle collection by diffusiophoresis and Stefan flow should also be a function of contacting power. However, there is no present reason to assume that the functions will be the same for different types of contactors.

In both the steel and pulp and paper industries, scrubber systems have been fitted with cooling towers or other contactors in which the gases are cooled and dehumidified.[26,30] These systems were installed for reasons other than attempts to increase collection efficiency, and apparently no effort has been made to determine whether there have been increments of efficiency resulting specifically from the condensation of water vapor.

In a very recent paper, Calvert et al.[6A] report an extension of the earlier work [6] on condensation scrubbing by a single sieve-plate collector. The investigators studied the collection of iron oxide aerosols by a three-plate bench-scale scrubber and a five-plate pilot-scale scrubber. The units were operated with countercurrent flow of water (entering cold), and the entering gas was saturated with water vapor at its inlet temperature. Each scrubber was operated at essentially the same gas pressure drop in all tests. As the quantity of water vapor condensed (g/g dry air) was increased, collection efficiency increased markedly.

Calvert et al,[6A] also presented a plot (reproduced here as Figure 24) that summarizes the results of a number of condensation scrubbing studies reported in the literature; penetrations are shown as functions of the amount of water vapor condensed in or injected into the respective scrubber systems (expressed as g/g dry gas). Where investigators carried out tests over ranges of condensation ratio, there are indicated reductions in the particulate penetration with increasing condensation ratio. The operating range observed in the present investigation has been added to the figure, appearing as the shaded vertical band. The condensation ratio used varied only slightly in the tests, but the range of values of the penetration was determined by the effective friction loss across the scrubber, which was the other major variable determining the penetration.

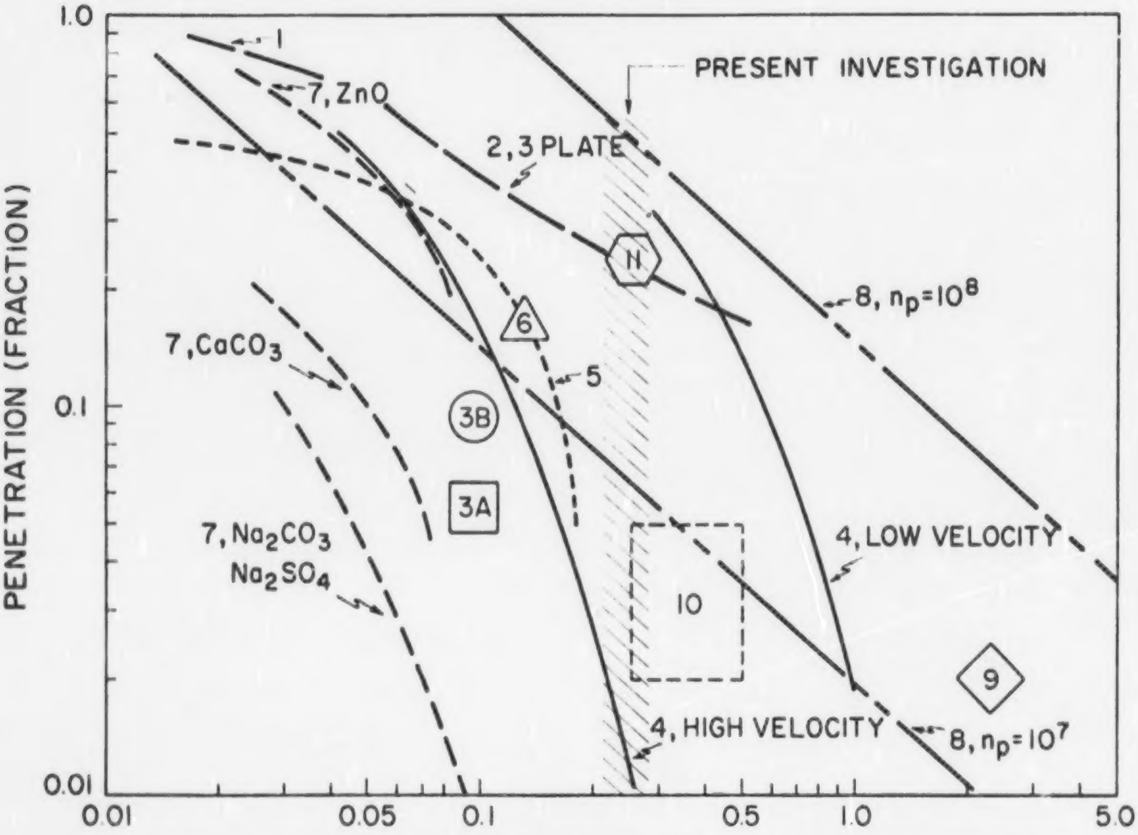


FIGURE 24 PERFORMANCE OF CONDENSATION SCRUBBERS—LITERATURE DATA (FIGURE 12, REF. 6A)—RANGE OF PRESENT INVESTIGATION ADDED

(Number on curves refer to references in Ref. 6A.)

REFERENCES

APPENDIX A

1. Behie, S. W., and J. M. Beeckmans, On the Efficiency of a Venturi Scrubber, Can. J. Chem. Eng. 51 (4), 430-533 (Aug. 1973).

2. Boll, R. H., Particle Collection and Pressure Drop in Venturi Scrubbers, Ind. Eng. Chem. Fundam. 12 (1), 40-50 (1973).

3. Calvert, Seymour, Venturi and Other Atomizing Scrubbers Efficiency and Pressure Drop, AIChE Journal 16 (3), 392-396 (May 1970).

4. Calvert, S., J. Goldshmid, D. Leith, and D. Mehta, Scrubber Handbook, Vol. I, A.P.T., Inc., Riverside, California (July 1972), EPA Contract No. CPA-70-95, NTIS: PB-213 016.

5. Calvert, S., J. Goldshmid, and David Leith, Scrubber Performance for Particle Collection, AIChE Symposium Series 70 (137), 357-364 (1974).

6. Calvert, S., J. Goldshmid, D. Leigh, and N. C. Jhaveri, Feasibility of Flux Force/Condensation Scrubbing for Fine Particulate Collection, EPA Rept. No. EPA-650/2-73-036 (Oct. 1973), NTIS: PB-227 307.

6A. Calvert, S., and N. C. Jhaveri, Flux Force/Condensation Scrubbing, Proc. EPA-APT Fine Particle Scrubber Symposium (May 28-30, 1974), pp. 86-118.

7. Fuchs, N., and A. Kirsch, The Effect of Condensation of a Vapor on the Grains and of Evaporation from Their Surface on the Deposition of Aerosols in Granular Beds, Chem. Eng. Sci. 20, 181-185 (1965).

8. Goldsmith, P., and F. G. May, Diffusiophoresis and Thermophoresis in Water Vapor Systems, Aerosol Science, Davies, C. N. (ed.), Academic Press, New York (1966), pp. 163-194.

9. Güntheroth, H., Schwebstoff-Nassabscheidung aus Gasen mit dem Venturi Scrubber, Fortschritt-Ber. VDI-Z Series 3, Issue 13 (1966).

10. Güntheroth, Hans, An Artificially Generated Aerosol for Wet Scrubbing Tests on a Semi-Industrial Scale, Staub-Reinhalt Luft (in English) 28 (11), 82-87 (Nov. 1968).

REFERENCES (continued)

11. Harmon, Robert Rogers, Removal of Suspended Matter from Industrial Gases, J. Inst. Fuel 11 (60), 514-527 (Aug. 1938).

12. Jepson, John C., Mass Transfer in Two-Phase Flow in Horizontal Pipelines, AIChE Journal 16 (5), 705-711 (Sept. 1970).

13. Kulic, E., and E. Rhodes, Chemical Mass Transfer in Co-Current Gas-Liquid Slug Flow in Helical Coils, Can. J. Chem. Eng. 52 (1), 114-116 (Feb. 1974).

14. Lapple, C. E., and H. J. Kamack, Performance of Wet Dust Scrubbers, Chem. Eng. Prog. 51 (3), 110-121 (Mar. 1955)

15. Meisen, A., A. J. Bobkowicz, N. E. Cooke, and E. J. Farkas, The Separation of Micron-Size Particles from Air by Diffusiophoresis, Can. J. Chem. Eng. 49 (4), 149-157 (Aug. 1971).

16. Melandri, C., V. Prodi, O. Rimondi, and G. Tarroni, Submicron Particle Precipitator Based on Water Vapor Condensation, Treat. Airborne Radioactive Wastes, Proc. Symp. 1968, 541-550

17. Reiss, L. Philip, Cocurrent Gas-Liquid Contacting in Packed Columns, I & EC Proc. Des. Develop. 6 (4), 486-599 (Oct. 1967).

18. Rozen, A. M., and V. M. Kostin, Collection of Finely Dispersed Aerosols in Plate Columns by Condensation Enlargement, Int. Chem. Eng. 7 (3), 464-467 (July 1967).

19. Semrau, Konrad T., Correlation of Dust Scrubber Efficiency, J. Air Poll. Control Assoc. 10 (3), 200-207 (June 1960).

20. Semrau, Konrad T., Dust Scrubber Design--A Critique on the State of the Art, J. Air Pollution Control Assoc. 13 (12), 587-594 (Dec. 1963).

21. Semrau, K. T., C. W. Marynowski, K. E. Lunde, and C. E. Lapple, Influence of Power Input on Efficiency of Dust Scrubbers, Ind. Eng. Chem. 50 (11), 1615-1620 (Nov. 1958).

22. Sparks, L. E., and M. J. Pilat, Effect of Diffusiophoresis on Particle Collection by Wet Scrubbers, Atmos. Environ. 4, 651-660 (1970).

23. Taheri, M., and G. F. Haines, Optimization of Factors Affecting Scrubber Performance, J. Air Poll. Control Assn. 19 (6), 427-431 (June 1969).

REFERENCES (concluded)

24. Taheri, M., S. A. Beg, and M. Beizaie, Gas Cleaning in a Wetted Butterfly Valve, J. Air Poll. Control Assn. 22 (10), 794-798 (Oct. 1972).

25. Taheri, M., S. A. Beg, and M. Beizaie, The Effect of Scale-Up on the Performance of High-Energy Scrubbers, J. Air Poll. Control Assn. 23 (11), 963-966 (Nov. 1973).

26. Vegeby, Anders, Hot Water from Recovery Boiler Stack Gas: SF Scrubber--MODO System, Pulp Paper Mag. Can. 69 (9), 68-74 (May 3, 1968).

27. Walker, A. B., Enhanced Scrubbing of Black Liquor Boiler Fume by Electrostatic Pre-Agglomeration: A Pilot Plant Study, J. Air Poll. Control Assn. 13 (12), 622-627 (Dec. 1963).

28. Walker, A. B., and R. M. Hall, Operating Experience with a Flooded-Disc Scrubber--a New Variable Throat Orifice Contactor, J. Air Poll. Control Assn. 18 (5), 319-323 (May 1968).

29. West, P. H., H. P. Markant, and J. H. Coulter, New Venturi Scrubber Developments. The Steam-Atomized Venturi, Tappi, 44 (10), 710-715 (Oct. 1961).

30. Willett, H. P., and D. E. Pike, Venturi Scrubber for Cleaning Oxygen Steel Process Gases, Iron & Steel Engr., 38 (7), 126-131 (July 1961).

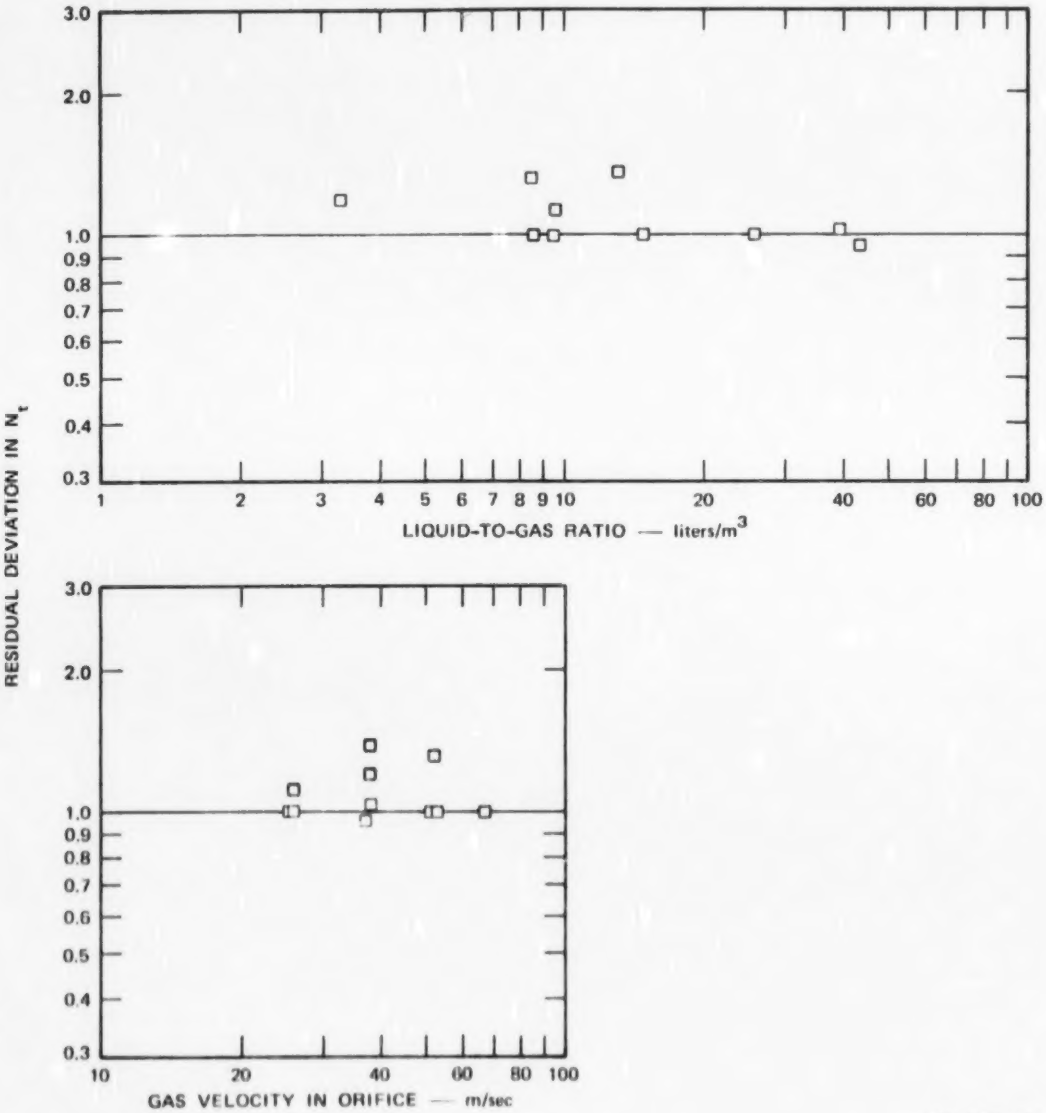
APPENDIX B

ANALYSIS OF EXPERIMENTAL DATA

The scrubber performance curves drawn through the data points in the various correlations were placed by eye, and not all points were accorded equal weight. Rather, judgments were made of the probable reliability of individual points and some points were essentially ignored. In general, the curve was selected to give the best appearing straight line over the widest possible range of pressure drop. When the data points in the low pressure drop range appeared to fall on a different curve, they were fitted (so far as possible) by separate straight lines.

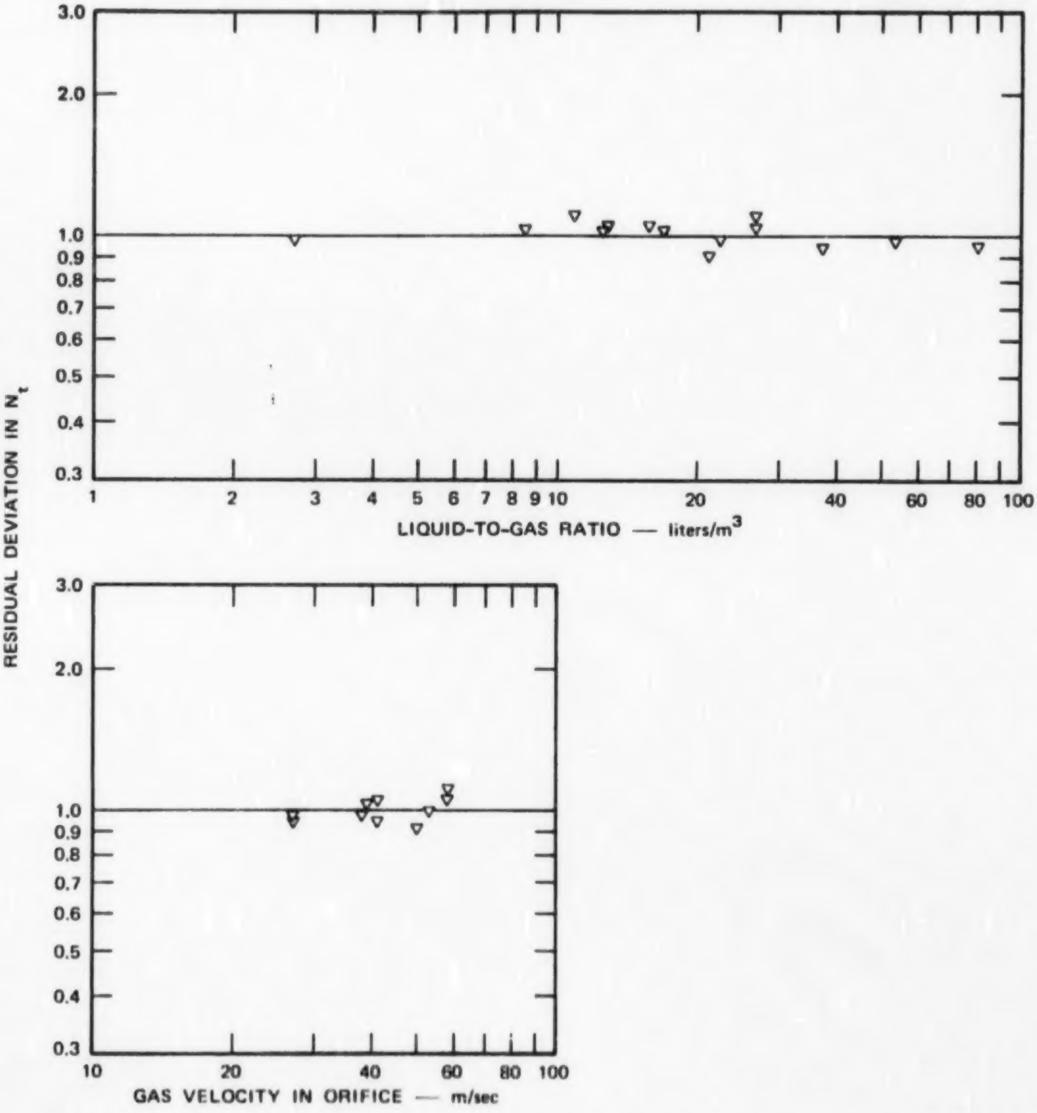
This procedure involved relatively little uncertainty in those cases where little scatter appeared in the data points and a straight line was clearly defined. For the Ambient Scrubbing tests, considerable scatter usually remained in the data even after they were rationalized by plotting according to ranges of aerosol generation rate. In these instances, the bias injected during curve fitting was substantially greater.

Although the Ambient Scrubbing tests were originally made with the intention of displaying systematically the effects (if any) of orifice gas velocity, liquid-to-gas ratio, and orifice size, the effort was largely frustrated by the variations in the aerosol. Thus, the individual correlations according to aerosol generation rates (Figure 6-10) were composed of data having somewhat random values of gas velocity and liquid-to-gas ratio. The transfer unit data were well rationalized by plotting them as functions of effective friction loss, without reference to orifice diameter, gas velocity, or liquid-to-gas ratio. This point is illustrated more clearly and forcefully by the plots in Figures 25-28,



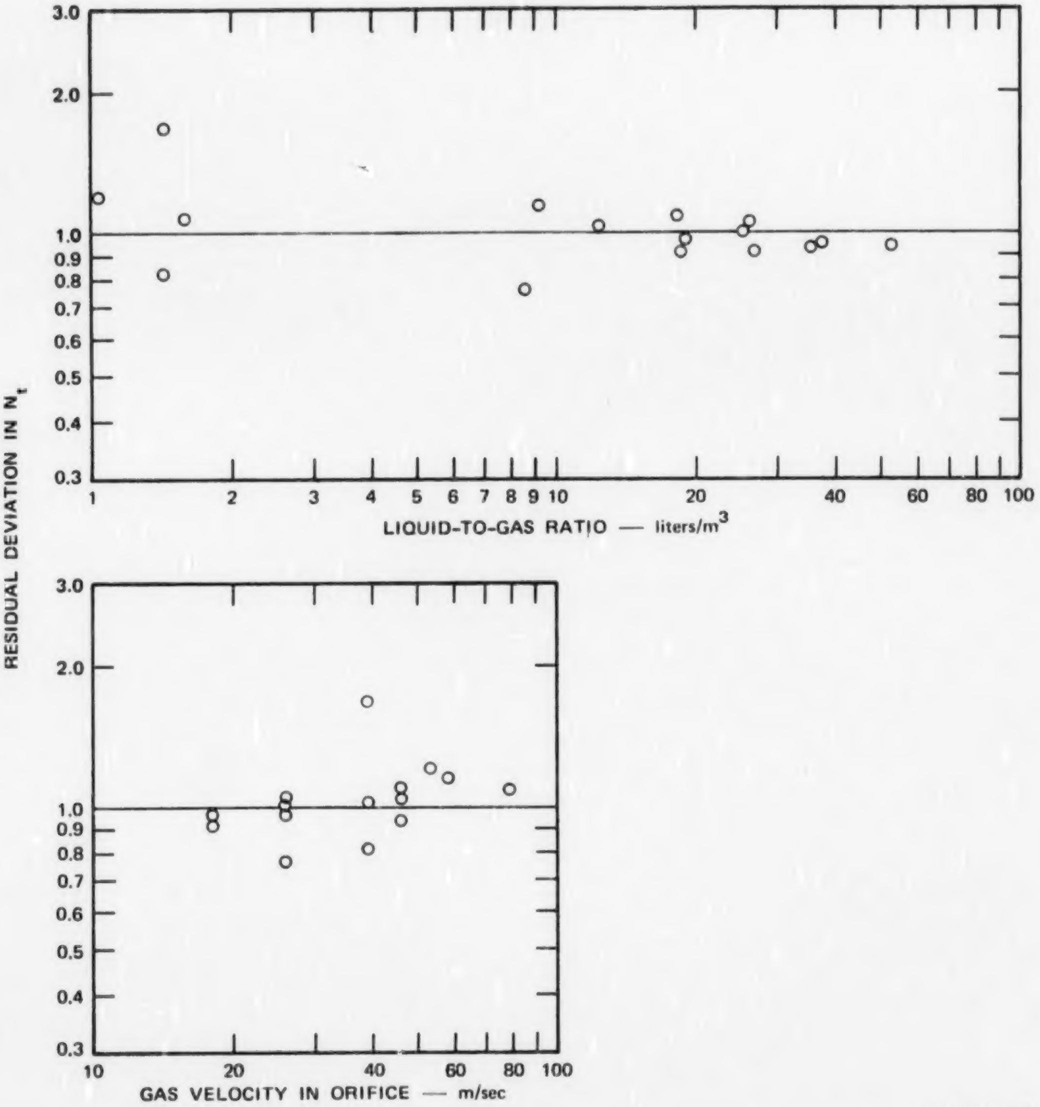
SA-2745-26

FIGURE 25 ANALYSIS OF RESIDUAL DEVIATIONS—AMBIENT SCRUBBING TESTS
Aerosol generation rates 750-1000 μg/min.



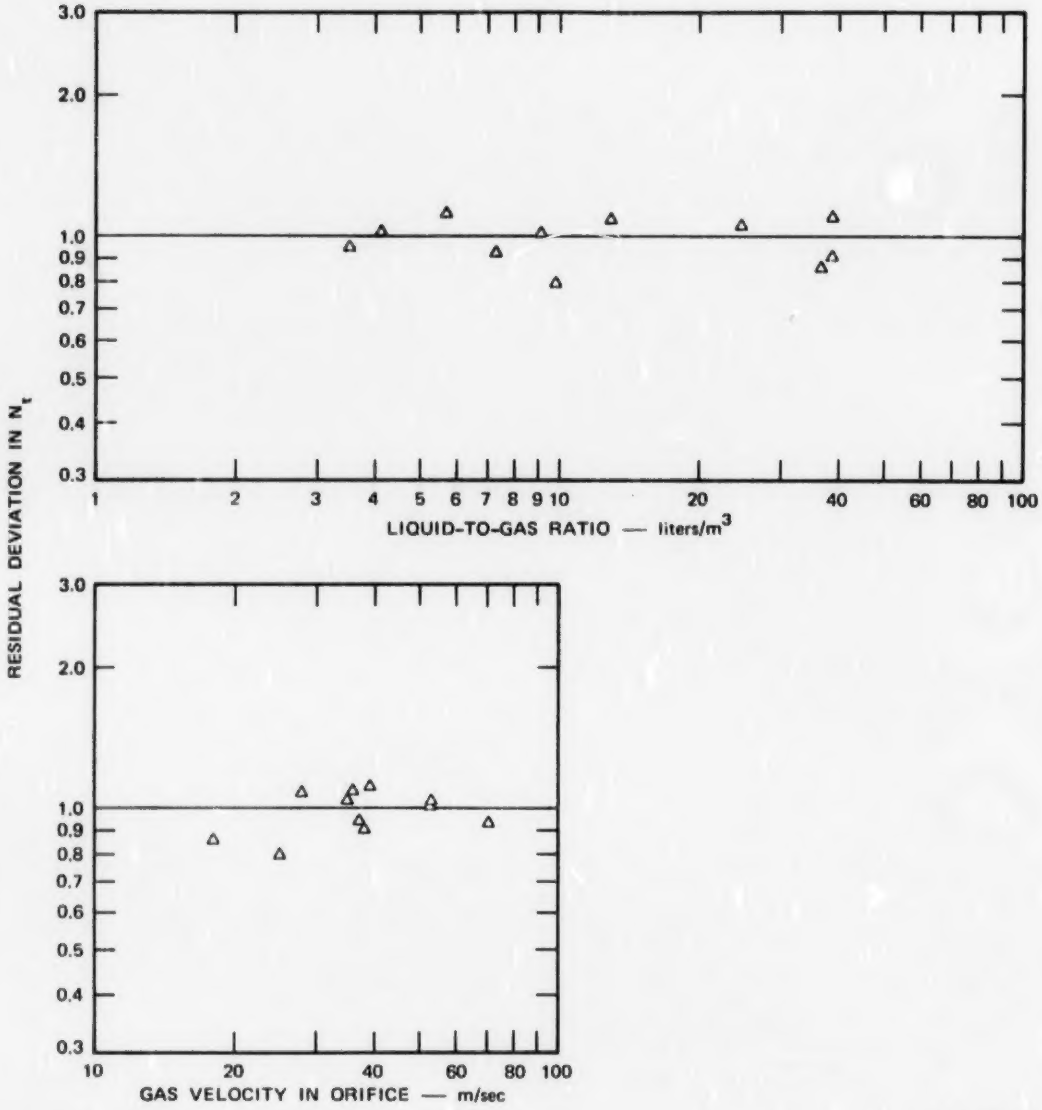
SA-2745-27

FIGURE 26 ANALYSIS OF RESIDUAL DEVIATIONS—AMBIENT SCRUBBING TESTS
Aerosol generation rates 1000-1200 μg/min.



SA-2745-28

FIGURE 27 ANALYSIS OF RESIDUAL DEVIATIONS—AMBIENT SCRUBBING TESTS
Aerosol generation rates 1200-1500 μg/min.



SA-2745-29

FIGURE 28 ANALYSIS OF RESIDUAL DEVIATIONS—AMBIENT SCRUBBING TESTS
Aerosol generation rates 1500-1900 μg/min.

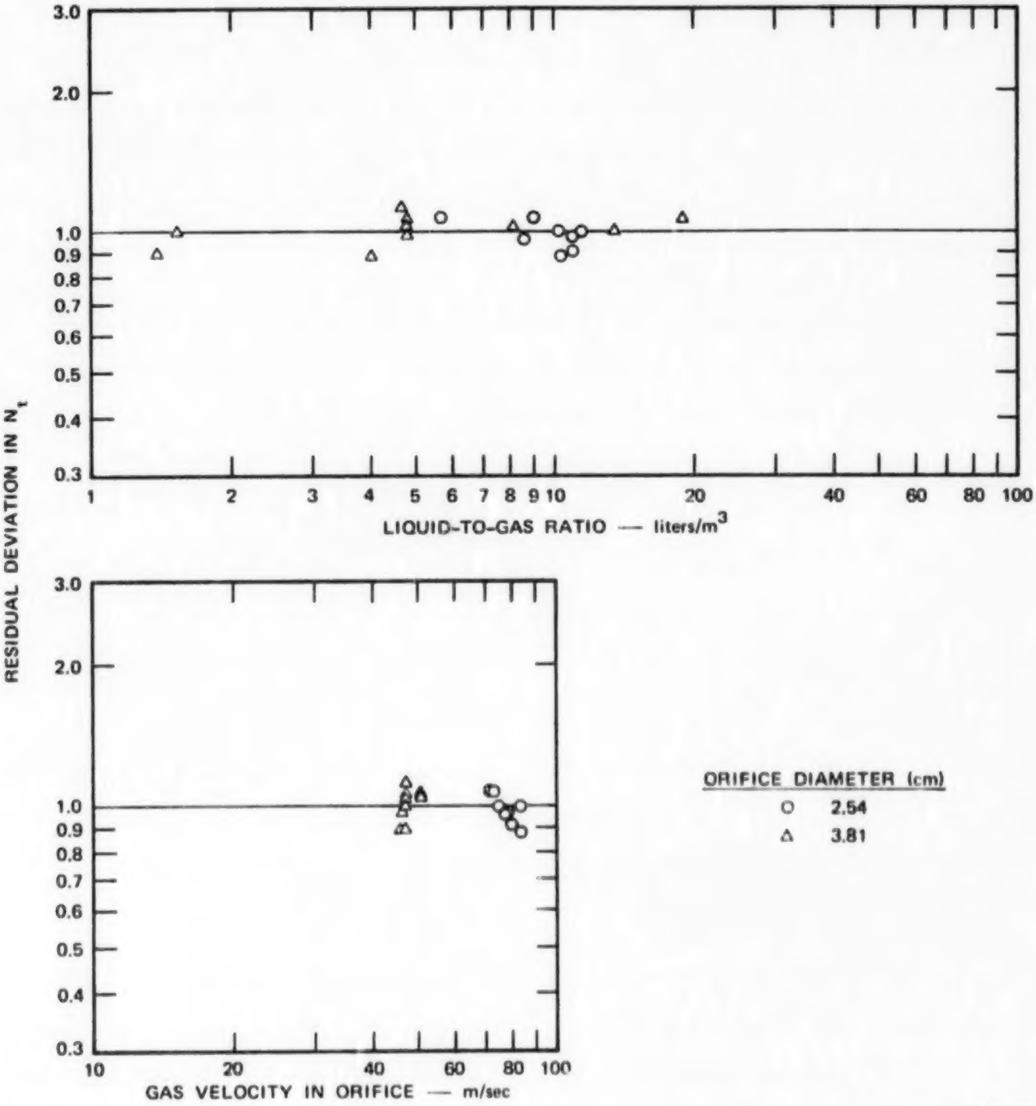
where the residual deviations of the data points from the correlation curves are plotted as functions of liquid-to-gas ratio and gas velocity in the contractor orifice.

The residual deviations were determined graphically, and laid off from the reference axis 1.0 on the same log-log grid used for the original plot. Any trends with liquid-to-gas ratio or gas velocity that are not reflected in the effective friction loss should thus be made readily visible.

The dispersion of the residuals in Figures 25-28 is exaggerated by the bias introduced in placing the original correlation curves. Nevertheless, no significant independent trends in performance with variations in liquid-to-gas ratio or gas velocity are indicated. The effects of these variables are evidently completely absorbed in the effective friction loss.

No such plots were made for the separate correlations in the low pressure drop regions of Figures 7 and 8, since the data in these regions were inadequate to define good correlation curves in the first place. No residuals were plotted for the correlations of Figure 6, since it was obvious by inspection that the residuals would be very small except for the one data point presumed to represent a systematically different aerosol.

In Figure 29, similar plots are presented for the residual deviations of the data points for the Adiabatic Saturation scrubbing tests with Aerosol A (Figure 13). In this case, the original correlation was generally better than those for the Ambient scrubbing tests. The absence of any significant trends in the residual deviations is again clear, even though the liquid-to-gas ratio--in particular--was varied over a range of nearly fourteenfold.



SA-2745-30

FIGURE 29 ANALYSIS OF RESIDUAL DEVIATIONS—ADIABATIC SATURATION SCRUBBING—AEROSOL A

APPENDIX C

POTENTIAL COMMERCIAL APPLICATION OF CONDENSATION SCRUBBING

The results of the present investigation as well as of earlier ones have indicated that the contacting power requirement for scrubbing of a given aerosol may be substantially reduced if condensation phenomena can be employed to enhance the more conventional scrubbing mechanisms. In addition to the reduction in contacting power, there is an additional saving on power that results from the cooling of the gas and the consequent reduction in the volume of the gas that must be handled by the induced-draft fan. Particularly in cases where the original gas has a high water vapor content, the condensation of the vapor as well as the reduction in temperature can combine to produce a major reduction in the gas volume that must be handled.

The use of gas cooling towers following some scrubbers on steel making furnaces (see Appendix A) has apparently been intended primarily to gain public relations advantages by eliminating steam plumes from stacks, but the saving of fan power may be of equal weight. Apparently it was (and perhaps still is) a common practice to discharge the cooling water from the towers directly to sewers, since the water contained relatively little particulate matter. However, if such discharges are stopped by water pollution control regulations (as they probably will be), the cooling water will itself have to be treated and recirculated after being cooled by direct or indirect means. In such a case, the economics of cooling and dehumidifying the scrubber exit gas will present a different and less favorable picture.

On the other hand, the cleaning and dehumidification of blast furnace gas for immediate or delayed use as fuel is a general necessity. Hence, the conditions for potential use of condensation scrubbing already exist in this case. A similar potential application exists where basic oxygen furnaces are equipped with noncombustion gas collection systems. When the offgas is accumulated for later use as fuel, it will--like blast furnace gas--have to be both cleaned and dehumidified. Yet another similar situation exists where gases from smelters, pyrite roasters, or other similar sources are used to make sulfuric acid by the contact process (see Appendix A). The feed gas to the contact plant must be thoroughly cleaned and dehumidified, and requirements for final gas cleanliness and dryness are more critical than those for blast furnace gas.

Gas cleaning and conditioning systems for blast furnace gas and acid-plant feed gas are already well developed and reasonably well standardized after long experience, even though they may still be far from optimum. Gas scrubbing systems for unburned BOF offgas are in commercial use, but apparently are not yet as well developed or standardized as in the other two applications. In all three of these applications of scrubbers, condensation mechanisms of particle collection may already be operative, but possibly not in optimum ways. If condensation phenomena can be used more effectively, it may require no more than relatively minor modifications of the systems to accomplish this.

A fourth possible application of condensation scrubbing is in the collection of fume from a Kraft black liquor recovery furnace (see Appendix A). This collection problem is a more conventional one than the others mentioned above. The gases already have high moisture contents (25 to 35% by volume), and in this respect are representative of a considerable number of industrial waste gases (e.g., gases from wet-process cement kilns and from lime kilns burning precipitated lime; tail gases from thermal phosphoric acid furnaces). Scrubbers are already extensively used on black liquor recovery furnace gases, either alone or in combination with electrostatic precipitators. Pulp mills utilize substantial amounts of low-level heat, particularly for heating water for pulp washing. Considerable use is already being made of scrubbers--particularly in Scandinavia--to heat water by contact with the hot gas from recovery furnaces, and this results in condensation of water from the gases. In such cases, condensation effects may be brought into play inadvertently, but apparently there are no operating installations that were designed deliberately to take advantage of condensation.

Still another possible application for condensation scrubbing is the cleaning of the flue gases from sewage sludge incinerators. Because of the high moisture contents of the sludge filter cakes being burned, the water vapor content of the flue gas is commonly equivalent to a saturation temperature of about 80°C. Scrubbing with sufficient water at ambient temperature will thus produce a large amount of condensation, which will increase the collection efficiency. However, the fly ash from the incinerators apparently contains little material that is fine enough in particle size to present a difficult collection problem. Therefore, there may not actually be a strong economic incentive to employ condensation scrubbing.

RECOMMENDED APPLICATION FOR TESTING

Scrubbing of black liquor recovery furnace gases appears to be by far the most advantageous application for a field demonstration of condensation scrubbing in a potential commercial application. It does not have the highly specialized aspects of the cleaning of blast furnace and BOF gases. The fume is of a relatively uniform nature and composition and is generated on a comparatively steady basis, and considerable information is already available on its scrubbing characteristics, including preliminary indications of possible improvements in performance realizable from use of condensation. Also, the use of low-level heat now wasted in pulp mills is becoming more attractive as the costs of fuel rise. There is already extensive experience with the use of commercial scrubbers, including observations that the performances of small and large units at the same contacting power level are essentially the same. Hence, it should be possible to apply system modifications developed on a pilot-plant scale to a full-scale commercial unit with minimum risk.

PILOT-PLANT SYSTEM

If a field demonstration is carried out it is recommended that the investigation be carried out on a pilot-plant basis with a scrubber unit (or units) having a gas flow capacity of about 850 m^3/hr (500 ft^3/min), measured at inlet conditions. Such a pilot plant is small enough to be operated with relative ease on a slip stream of gas from a commercial recovery furnace without interfering with, or being unduly interfered with, by the operational requirements of the furnace. Modifications of the experimental system can be made quickly and at modest costs. At the largest, the pilot plant gas capacity should not exceed 1700 m^3/hr (1000 ft^3/min). The fan capacity should be adequate to handle scrubber pressure drops of up to at least 1800 mm WC (70 inches WC).

A minimum program can be elected, or an optional expanded program can be undertaken at higher cost. If the expanded program is adopted, the following major system components will be required:

A. A simple baffle chamber with a spray nozzle located at the inlet. The chamber should be designed for a maximum superficial gas velocity of about 1.0 m/sec (3 ft/sec) and to give a nominal gas residence time of up to three seconds.

B. A variable-orifice scrubber with a cyclone entrainment separator.

C. A scrubber with alternative variable-orifice and pipeline contactors and a cyclone entrainment separator.

D. A countercurrent packed tower with provisions for installation of up to 4 m (13 ft) of grid packing. The tower should be designed for a maximum superficial gas velocity of 1.5 m/sec (5 ft/sec). It should be equipped with a louvre- or herringbone-type of entrainment separator, designed for a maximum superficial gas velocity of 1.5 m/sec (5 ft/sec).

E. Induced-draft fan.

F. Water-circulating system, including pumps and shell-and-tube heat exchangers for cooling recirculated scrubbing water.

If the minimum program is elected, then A, the baffle chamber, and D, the packed tower, can be eliminated. The collectors in the system should be so equipped that they can be fitted together in any desired combination, although only certain combinations are contemplated. Provisions should be made to sample the gas not only at the inlet and outlet of the system but between any units placed in series.

MINIMUM PROGRAM

The basic, or minimum program will make use of the two cocurrent-contact scrubbers B and C in the following steps:

The reference operating condition will be adiabatic saturation scrubbing of the gas, using the variable-orifice scrubber C. Sufficient data will be taken to establish a scrubber performance curve for a wide range of effective friction loss (up to at least 1500 mm WC).

- Scrubber C will then be operated with cold water as a condensation scrubber, to give an exit gas temperature of 50°C. Scrubber performance curves will be established for both the orifice and pipeline contactors, if the two devices should give different curves.

- Scrubbers B and C will be used in series, with B operated as a low-energy adiabatic saturator and with C operating on the presaturated gas as a condensation scrubber with an exit gas temperature of $50^{o}C$. The efficiencies of each scrubber individually and of the two in combination will be determined. Sufficient data will be taken to establish scrubber performance curves over the range of effective friction loss up to at least 1500 mm WC total (for both scrubbers).

EXPANDED PROGRAM

The expanded program will incorporate the minimum program, together with additional experiments using the baffle chamber A and the countercurrent packed tower D.

- The baffle chamber will be used as a gas quencher rather than as a scrubber. It will be followed by Scrubber C, used in both adiabatic saturation scrubbing and condensation scrubbing. The baffle chamber will be fed with only enough cold water to bring the inlet gas to saturation and--perhaps--to cause fume particles to nucleate droplet formation. If significant buildup of the particles takes place, it may be revealed by the performance curves for the scrubber.
- The countercurrent packed tower D should represent a low-energy device that nonetheless will produce a large amount of water vapor condensation. It will be operated in series with, and downstream of, Scrubber C, which will be operated as an adiabatic saturation scrubber at two levels of effective friction loss but at the same gas flow rate. The overall efficiency and the separate efficiencies of each

device will be determined. For each level of prescrubber effective friction loss, the efficiency of the packed tower will be studied as a function of water rate and amount of water vapor condensed.

PROGRAM REQUIREMENTS

If the sizes of the pilot-plant units are kept within the capacity range of 850 m^3/hr, the cost of the foregoing program can be kept within a relatively modest figure. For the minimum program, the costs of the equipment and experimental work could probably be kept within about $250-275,000. Administrative and other costs involved in carrying on a program at the plant site of a cooperating Kraft mill could add substantially to this estimate. The expanded program would perhaps add $50-75,000 to the cost.